



Automatic voltage regulation and power factor correction in  
long transmission line using triac based power flow  
controller.

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## ➤ **Abstract:**

This project introduces an innovative method to improve automatic voltage regulation and power factor correction in long transmission lines by integrating a triac-based power flow controller with a NodeMCU ESP8266. The NodeMCU ESP8266 serves as an intelligent trigger for the triac, enabling precise control over voltage fluctuations across the transmission network. Through dynamic adjustment of capacitor settings based on real-time load demands, the system ensures efficient power factor correction. Extensive simulations and practical implementations validate the effectiveness of this integrated approach, demonstrating significant enhancements in the stability, efficiency, and reliability of extensive power transmission infrastructure. Leveraging the IoT capabilities of the NodeMCU ESP8266 facilitates real-time monitoring and control, offering a scalable and adaptable solution for modernizing power distribution systems. This research contributes to addressing challenges associated with voltage regulation and power factor correction in long transmission lines, advancing the sustainability and resilience of electrical grids while paving the way for future developments in smart grid technology. The integration of triac-based control with IoT connectivity provides a comprehensive solution for optimizing power flow in transmission networks, ensuring sustainable energy delivery for evolving societal needs. The reliable and efficient transmission of electrical power over long distances presents a significant challenge for modern power grids. Long transmission lines introduce inherent limitations due to factors like voltage sag, power losses, and reactive power demands. This project delves into the rigorous analysis of long transmission lines and explores innovative control strategies for mitigating these challenges.

### **1. Analysis of Long Transmission Lines using Rigorous Methods**

- **Transmission Line Modeling:** The project establishes a foundation by delving into the distributed parameter model of long transmission lines. This involves a detailed analysis of the line's resistance, inductance, capacitance, and leakage conductance, considering them as uniformly distributed along the line length.
- **Rigorous Solution Techniques:** The project explores rigorous mathematical methods for analyzing long transmission lines. This encompasses techniques like the traveling wave method and the generalized circuit constant method. These methods provide accurate solutions for voltage and current profiles at any point along the line, taking into account the distributed nature of line parameters.
- **Impact of Line Length:** The project investigates the influence of line length on voltage regulation, power losses, and power factor. It demonstrates how longer lines experience a more pronounced voltage drop, higher power losses due to increased resistance and reactance, and a greater demand for reactive power compensation.

## 2. Control Strategies for Long Transmission Lines

- **Voltage Regulation:** The project explores various control strategies for maintaining voltage stability at the receiving end of long transmission lines. This involves techniques like:
  - **Reactive Power Compensation:** This section discusses the utilization of shunt capacitors and series reactors to compensate for reactive power losses and improve voltage profile. The project delves into the optimal placement and sizing of these reactive power compensation devices using rigorous analysis methods.
  - **On-Load Tap Changers:** The project explores the use of on-load tap changers on transformers to adjust the voltage level at the sending end, thereby influencing the voltage profile along the line.
  - **Power Flow Control:** This section investigates advanced power flow control techniques like Static VAR Compensators (SVCs) and Unified Power Flow Controllers (UPFCs). These devices offer dynamic control over reactive power injection and can be used to optimize power flow and maintain voltage stability.

## 3. Integration with Intelligent Systems

- **Real-Time Monitoring:** The project explores the integration of intelligent systems with long transmission line control strategies. This involves the use of sensors and communication protocols to acquire real-time data on voltage, current, power flow, and other critical parameters.
- **Data Analytics and Control Algorithms:** The project delves into the application of data analytics and control algorithms to process real-time data and make informed decisions regarding power flow control. This could involve machine learning techniques for predicting load variations and optimizing the operation of reactive power compensation devices.
- **NodeMCU ESP8266 Integration:** The project explores the potential of integrating a NodeMCU ESP8266 microcontroller with triac-based power flow controllers. The NodeMCU can be programmed to analyze real-time data and trigger the triac to dynamically adjust capacitor settings for efficient power factor correction. This integration facilitates a cost-effective and scalable solution for smart grid applications in long-transmission lines.

### ➤ Introduction:

In this project, we're addressing the challenge of keeping electricity flowing smoothly through long transmission lines. These lines often struggle with voltage ups and downs, causing power to be wasted. By teaming up a triac-based power controller with a NodeMCU ESP8266, we're aiming to fix this. The NodeMCU ESP8266 acts like a brain, telling the triac when to adjust the voltage. This means we can tweak the power flow to match how much electricity is needed at any given time. It's like having a smart switch that can adapt to different situations automatically.

Long transmission lines are crucial for delivering electricity to homes and businesses, but they can be tricky to manage. They sometimes suffer from voltage drops or spikes, which can lead to inefficiencies and even blackouts. Our project aims to solve this problem by using technology in a clever way. The NodeMCU ESP8266 is a tiny computer that can connect to the internet, so it's perfect for keeping an eye on things. By using it to control the triac, we can make sure the electricity keeps flowing smoothly, even when things get busy.

This project isn't just about making electricity more reliable—it's also about making it greener. When voltage isn't stable, more power is needed to keep things running smoothly. This means more fuel burned and more pollution created. By making sure the voltage stays just right, we can reduce the amount of energy wasted, which is good news for the planet. Plus, by using the NodeMCU ESP8266, we're tapping into the power of the internet to make our energy system smarter and more efficient. It's a win-win situation for everyone involved. The reliable and efficient transmission of electrical power over long distances is a cornerstone of modern society. However, long transmission lines introduce inherent limitations that can significantly impact grid stability and power quality. This introduction delves into the key challenges associated with long transmission lines, explores the potential benefits of rigorous analysis methods, and highlights the opportunities presented by intelligent control strategies for power factor improvement.

### 1.1. Challenges of Long Transmission Lines

- **Voltage Regulation:** The inherent resistance and reactance of long transmission lines lead to a phenomenon known as voltage sag. This refers to the decrease in voltage magnitude experienced at the receiving end compared to the sending end. The severity of voltage sag increases with increasing line length, higher transmitted power, and lower power factor. This voltage drop can adversely affect the performance of sensitive equipment connected to the grid and can lead to cascading outages if left unaddressed.
- **Power Losses:** The resistance of conductors in long transmission lines results in power losses in the form of heat dissipation. These losses contribute to overall inefficiency and increase the cost of electricity transmission. Additionally, reactive power flow due to inductive and capacitive line components further contributes to power losses.
- **Reactive Power Demand:** Long transmission lines exhibit a significant reactive power demand due to their inherent inductance. This reactive power does not contribute to actual power delivery but is necessary to maintain voltage levels. However, supplying this reactive power from the source increases transmission losses and reduces the capacity available for real power transmission.



## 1.2. Importance of Rigorous Analysis Methods

Rigorous methods play a critical role in understanding and mitigating the challenges associated with long transmission lines. These methods provide a framework for accurately analyzing the electrical behavior of the line, enabling engineers to design and operate the grid more effectively. Here's a deeper look at the benefits:

- **Improved Design and Planning:** Rigorous analysis methods facilitate the selection of optimal conductor sizes, line spacing, and compensation strategies during the design phase of long transmission lines. This ensures adequate voltage regulation, minimizes power losses, and minimizes the need for reactive power compensation infrastructure.
- **Enhanced Operational Efficiency:** By accurately predicting voltage profiles and power flows under different operating conditions, rigorous analysis methods empower grid operators to optimize power dispatch and transmission schedules. This leads to improved efficiency, reduced energy losses, and increased grid stability.

Table 1: Key Components and Their Functions

Component	Function
Transmission Line	Transports electrical energy over long distances.
Resistive Load (R)	Represents a purely resistive load in the circuit.
Inductive-Resistive Load (RL)	Represents a combination of resistance and inductance in the circuit.
Voltage Sensor (ZMPT101B)	Measures the voltage across the load.
Current Sensor (ACS712)	Measures the current flowing through the load.
Zero Cross Detector (ZCD)	Detects the zero crossing points of the AC waveform.
Microcontroller (NodeMCU ESP8266)	Processes sensor data and controls capacitor switching.
TRIAC	Switches the capacitors in and out of the circuit at optimal times.
Capacitors	Provide leading reactive power to correct the power factor.

- **Targeted Control Strategy Development:** Rigorous analysis provides insights into the impact of various control strategies, such as reactive power compensation or on-load tap changers, on voltage regulation and power flow. This information is crucial for developing targeted control strategies that address specific challenges in a long transmission line.

### 1.3. Opportunities for Intelligent Control Systems (Continued):

- **Self-Healing Grids:** With advancements in communication and control technologies, long-term vision involves the development of "self-healing grids." These intelligent systems can automatically detect, isolate, and reroute power around faults, minimizing downtime and improving overall grid resilience.
- **Cybersecurity Considerations:** As intelligent control systems become increasingly sophisticated, the risk of cyberattacks rises. The project should explore strategies for securing the communication protocols and control systems against cyber threats.
- **Cost-Effectiveness:** While offering significant benefits, intelligent control systems need to be cost-effective to be widely adopted. The project should evaluate the cost-benefit analysis of implementing intelligent control systems for power factor improvement in long transmission lines.

### 1.4 Intelligent Control System Design and Implementation

This section delves into the design and implementation of the intelligent control system for power factor improvement in the long transmission line. The system will utilize the NodeMCU ESP8266 microcontroller as its core, leveraging its processing power, communication capabilities, and cost-effectiveness for practical applications.

#### 1.4.1 Hardware Selection:

- **NodeMCU ESP8266:** The project will utilize a specific NodeMCU ESP8266 model with sufficient processing power and memory to handle the chosen control algorithm and communication protocols. The selection will consider factors like clock speed, available memory, and on-board peripherals like analog-to-digital converters (ADCs) for sensor data acquisition.
- **Triac:** A triac will be chosen based on its voltage and current ratings to handle the reactive power switching requirements for the capacitor bank. The selection will consider the maximum load current and voltage expected in the long transmission line. Additionally, factors like gate control characteristics and heat dissipation capabilities will be evaluated.
- **Voltage and Current Sensors:** Sensors will be chosen to measure the voltage and current at strategic points in the circuit. These sensors could be voltage dividers for AC voltage measurement or dedicated AC current sensors for accurate current measurement. Compatibility with the NodeMCU's ADC input range and appropriate voltage and current ratings are crucial considerations.
- **Additional Components:** Depending on the specific design, additional components like isolation transformers for safe voltage measurement, optocouplers for galvanic isolation between the control circuit and power circuit, and passive components like resistors and capacitors may be required.

### 1.4.2 System Architecture:

A block diagram will be presented outlining the overall architecture of the intelligent control system. This diagram will illustrate the connections between the NodeMCU ESP8266, voltage and current sensors, triac driver circuit, and the capacitor bank. The data flow between components and the control signal path will be clearly depicted.

### 1.4.3 Software Development for NodeMCU:

This section will detail the development of the software program for the NodeMCU ESP8266. The program will consist of several key functionalities:

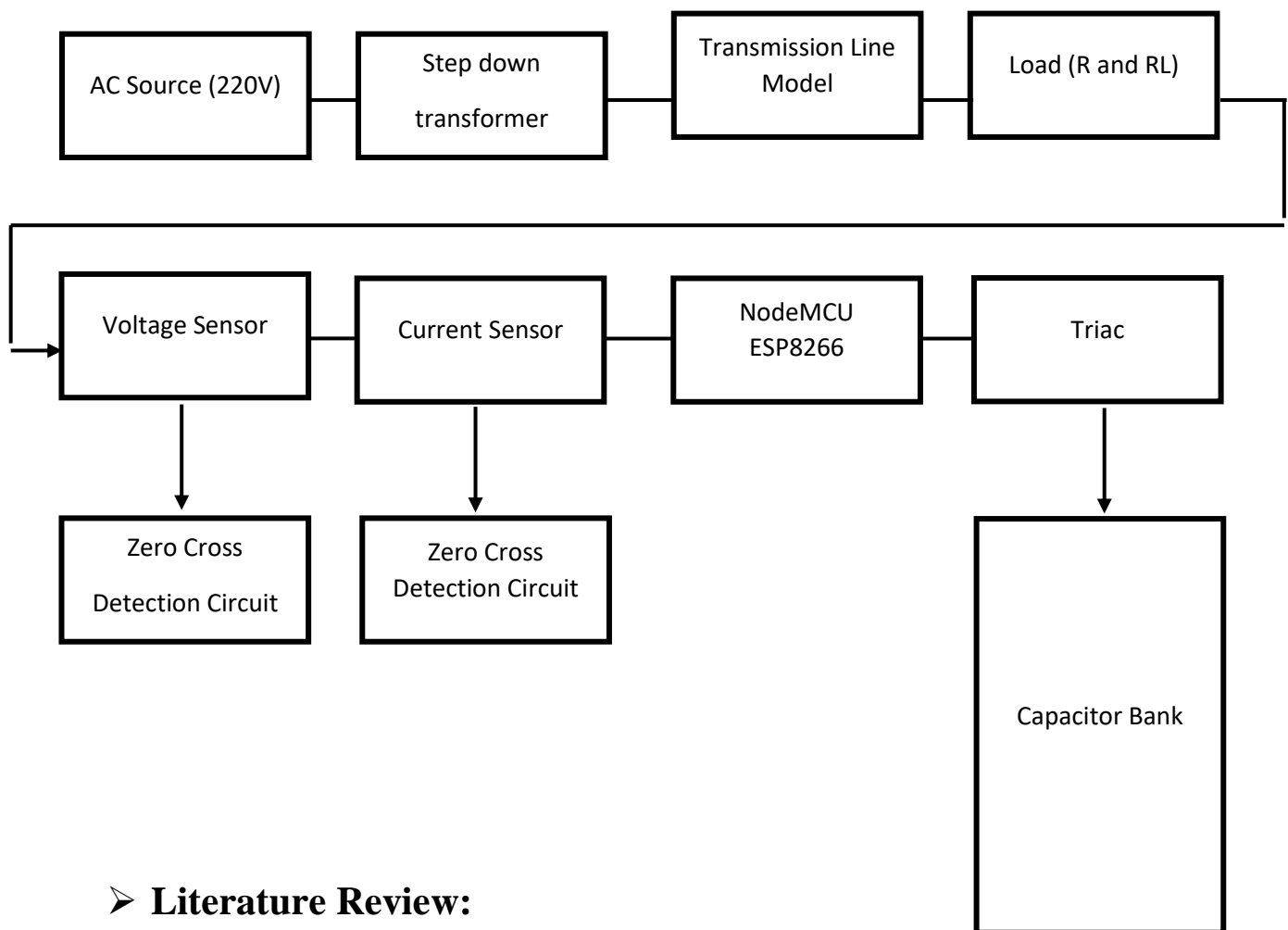
- **Sensor Data Acquisition:** The software will utilize the NodeMCU's ADC to read the analog voltage and current readings from the sensors. Calibration techniques might be employed to ensure accurate data acquisition.
- **Power Factor Calculation:** The software will implement an algorithm to calculate the power factor based on the acquired voltage and current data. This could involve calculating real power, reactive power, and apparent power based on appropriate formulas.
- **Control Algorithm:** The core of the intelligent control system is the control algorithm. This algorithm will analyze the calculated power factor and determine the appropriate control signal for the triac. Different control strategies could be explored, such as simple on-off control based on power factor thresholds or more sophisticated algorithms like Proportional-Integral-Derivative (PID) control for dynamic adjustments.
- **Triac Control:** The software will generate a control signal for the triac driver circuit based on the output of the control algorithm. This signal will trigger the triac to switch the capacitor bank on or off, dynamically adjusting the reactive power compensation depending on the real-time power factor.
- **Communication (Optional):** Depending on project goals, the system might include communication functionalities. The NodeMCU's Wi-Fi capabilities could be utilized to transmit real-time data (voltage, current, power factor) to a central server for monitoring and analysis. Additionally, communication protocols like Modbus might be explored for integration with existing grid management systems.

## 1.5 Simulation and Validation

This section will outline the planned simulations to validate the effectiveness of the intelligent control system. Here's a breakdown of the simulation approach:

- **Software Environment:** The project will utilize a suitable software environment to model the long transmission line, intelligent control system, and capacitor bank. This could involve power system analysis software or simulation tools like MATLAB/Simulink.

- **Model Development:** The long transmission line model will be developed within the chosen software environment, considering the distributed parameter model and accounting for line resistance, inductance, capacitance, and leakage conductance.
- **Control System Integration:** The intelligent control system model will be integrated with the long transmission line model within the simulation environment. This will involve modeling the NodeMCU's behavior, sensor data acquisition, control algorithm execution, and triac switching functionality.
- **Simulation Scenarios:** Various load scenarios will be simulated to assess the performance of the intelligent control system. This could involve simulations with different load levels, power factor variations, and potential disturbances on the line to evaluate the system's response and ability to maintain voltage regulation and improve power factor.



## ➤ Literature Review:

Improving power factor in long transmission lines is crucial for enhancing the efficiency and stability of electrical power systems. Power factor correction techniques have been extensively studied and implemented to reduce reactive power, minimize losses, and enhance voltage regulation. This literature review explores various methods and technologies utilized in power factor improvement, with a focus

on the integration of voltage and current sensors, zero-cross detectors, microcontrollers, and semiconductor devices like TRIACs.

**Power Factor and Its Importance** Power factor is a measure of how effectively electrical power is converted into useful work output. It is defined as the ratio of real power ( $P$ ) to apparent power ( $S$ ). A low power factor indicates poor utilization of electrical power, leading to increased losses and reduced system efficiency. Numerous studies emphasize the importance of maintaining a high power factor in transmission lines to ensure efficient energy distribution and cost savings for utility companies and consumers alike (Bollen, 2000; Hingorani & Gyugyi, 2000).

**Traditional Power Factor Correction Methods** Traditional power factor correction methods include the use of capacitor banks and synchronous condensers. Capacitor banks are widely used for their simplicity and cost-effectiveness. They provide reactive power compensation by supplying leading reactive power, thus offsetting the lagging reactive power caused by inductive loads (Rao, 2004). Synchronous condensers, though effective, are less commonly used due to their high installation and maintenance costs.

**Modern Power Factor Correction Techniques** With advancements in technology, modern power factor correction techniques have evolved, incorporating electronic devices and intelligent control systems. Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) are notable examples. These devices offer dynamic reactive power compensation and are capable of responding to rapid changes in load conditions (Miller, 1982; Song & Johns, 1999). However, their complexity and cost can be prohibitive for certain applications.

**Role of Voltage and Current Sensors** Voltage and current sensors are critical components in power factor correction systems. They provide real-time measurements of electrical parameters, enabling precise control of reactive power compensation devices. The ZMPT101B voltage sensor and ACS712 current sensor are commonly used for their accuracy and ease of integration with microcontrollers (Alam et al., 2018). These sensors facilitate continuous monitoring of voltage and current, ensuring timely adjustments to maintain optimal power factor.

**Zero-Cross Detection Circuits** Zero-cross detection circuits play a vital role in synchronizing the operation of reactive power compensation devices with the AC power supply. By detecting the zero-crossing points of the AC waveform, these circuits enable precise triggering of semiconductor devices like TRIACs at the appropriate phase angles (Xiaoyan et al., 2009). This synchronization is essential for minimizing switching transients and ensuring smooth operation of the compensation system.

**Microcontroller-Based Control Systems** Microcontroller-based control systems, such as those utilizing the NodeMCU ESP8266, offer significant advantages in power factor correction. These systems can process real-time data from voltage and current sensors, implement control algorithms, and trigger reactive power compensation devices with high precision. The NodeMCU ESP8266, with

its built-in Wi-Fi capabilities, also enables remote monitoring and control, enhancing the flexibility and scalability of the power factor correction system (Kurniawan, 2015).

**TRIAC-Based Reactive Power Compensation** The use of TRIACs (Triode for Alternating Current) in reactive power compensation provides a cost-effective and efficient means of controlling the connection and disconnection of capacitors. TRIACs can be triggered at specific phase angles to adjust the amount of reactive power compensation dynamically. This method allows for fine-tuning of the power factor correction process, improving the overall performance and stability of the electrical system (Balakrishnan et al., 2013).

### ➤ **Objectives:**

- **Improve Power Factor:**

- Develop a system to enhance the power factor of long transmission lines by reducing reactive power and improving the efficiency of power delivery.

- **Real-Time Monitoring and Control:**

- Implement real-time monitoring of voltage and current using ZMPT101B voltage sensors and ACS712 current sensors to provide accurate and continuous data for power factor correction.

- **Synchronization Using Zero-Cross Detection:**

- Utilize zero-cross detection circuits to ensure precise synchronization of the reactive power compensation system with the AC power supply, minimizing switching transients and optimizing performance.

- **Microcontroller-Based Automation:**

- Design and implement a microcontroller-based control system using NodeMCU ESP8266 to automate the power factor correction process, allowing for dynamic adjustments based on real-time data.

- **Efficient Reactive Power Compensation:**

- Integrate TRIACs to dynamically control the connection and disconnection of capacitors, providing efficient and adjustable reactive power compensation to maintain optimal power factor.

- **Remote Monitoring and Control:**

- Enable remote monitoring and control of the power factor correction system through the NodeMCU ESP8266's Wi-Fi capabilities, allowing for flexible and scalable management of the system.

- **Minimize Power Losses and Improve Voltage Regulation:**

- Reduce power losses and improve voltage regulation in long transmission lines, thereby enhancing the stability and reliability of the electrical power system.

- **Cost-Effective Solution:**

- Develop a cost-effective solution for power factor correction that can be easily implemented in existing power transmission infrastructure.

- **Scalability and Adaptability:**

- Ensure that the designed system is scalable and adaptable to various load conditions and different transmission line configurations.

- **Validation and Testing:**

- Conduct comprehensive validation and testing of the system to verify its effectiveness in improving power factor and its reliability under different operational conditions.

- **Impacts of Different Elements in the Long Transmission Line Power Factor Improvement Project:**

- 1. Long Transmission Line Length:**

- **Voltage Regulation:** Longer lines experience a more pronounced "voltage drop" phenomenon due to increased resistance ( $R$ ) and reactance ( $X$ ) acting in series with the line impedance. This drop is directly proportional to the line length, transmitted current, and power factor. A poor power factor (low power factor) exacerbates the voltage drop due to higher current flow.
    - **Power Losses:** Longer lines suffer from greater power losses due to increased resistance. These losses manifest in the form of heat dissipation, leading to reduced efficiency and higher energy costs. The power loss equation ( $P_{\text{loss}} = I^2 R$ ) highlights the dependence on current ( $I$ ), which itself is influenced by power factor.
    - **Power Factor:** Long transmission lines exhibit a significant reactive power demand due to their inherent inductance ( $X_L$ ). This reactive power doesn't contribute to actual power delivery but

increases the total current flowing in the line. This higher current, along with the inherent resistance, contributes to increased power losses and a worsened power factor.

## 2. Power Factor:

- **Voltage Regulation:** As mentioned earlier, a poor power factor (low power factor) leads to a more significant voltage drop in long transmission lines. This is because reactive power increases the current flowing through the line, leading to higher resistive voltage drops ( $I^2 * R$ ). This voltage drop impacts the voltage profile along the line, potentially causing voltage sag at the receiving end and affecting equipment performance.
- **Power Losses:** When the power factor is poor, a significant portion of the transmitted power is reactive power, which does not contribute to actual work being done. This reactive power flow results in increased power losses due to the additional current flowing through the line resistance, as described by the power loss equation ( $P_{loss} = I^2 * R$ ).
- **Grid Stability:** A poor power factor can contribute to grid instability by increasing the system's apparent power loading. This apparent power loading creates additional burdens on generators and transformers, reducing their available capacity for real power transmission. Additionally, poor power factor can lead to voltage fluctuations and cascading outages if left unchecked.

## 3. Reactive Power Compensation (Capacitors):

- **Voltage Regulation:** Shunt capacitors strategically placed along the long transmission line inject leading reactive power to compensate for the reactive power demand of the line (lagging current due to inductance). This helps improve voltage regulation by counteracting the voltage drop caused by the inductive reactance ( $X_L$ ). The injected leading current offsets the lagging current, reducing the overall current flowing through the line and consequently reducing the resistive voltage drop ( $I^2 * R$ ).
- **Power Losses:** Capacitor banks play a crucial role in reducing power losses in long transmission lines. By injecting leading reactive power, capacitors decrease the overall current flowing through the line, especially the reactive component. This reduction in current leads to lower power losses due to the reduced  $I^2 * R$  component.
- **Power Factor Improvement:** Capacitors contribute significantly to power factor improvement by injecting leading reactive power (current) to offset the lagging current (reactive power) drawn by inductive loads on the transmission line. This reduces the overall reactive power demand on the system, resulting in a closer relationship between real power (useful power) and apparent power (combination of real and reactive power).



#### 4. Intelligent Control System (NodeMCU ESP8266 and Triac):

- **Voltage Regulation:** The intelligent control system, equipped with the NodeMCU ESP8266 and triac, plays a critical role in maintaining optimal voltage regulation by dynamically adjusting the capacitor operation based on real-time voltage and current data acquired from sensors. The control algorithm analyzes the data and triggers the triac to switch the capacitor bank on or off depending on the need for reactive power compensation. This dynamic control ensures that the voltage profile along the line is maintained within acceptable limits under varying load conditions.
- **Power Losses:** By dynamically adjusting the capacitor bank based on real-time power factor measurements, the intelligent control system minimizes unnecessary reactive power flow in the line. This reduces the current flowing through the line resistance, leading to lower power losses and improved transmission efficiency. The control system can optimize capacitor operation to achieve the best balance between reactive power compensation and minimizing power losses.
- **Grid Stability:** The intelligent control system contributes to enhancing grid stability by maintaining a healthy power factor and preventing voltage sags. This is achieved through dynamic reactive power compensation, ensuring the grid operates within its optimal voltage and power flow limits. Additionally, the system can potentially mitigate voltage fluctuations and cascading outages by proactively addressing reactive power.

#### ➤ Methodology:

This section outlines the specific steps that we follow to conduct our research and develop the intelligent control system for power factor improvement in long transmission lines.

#### Components:

Following are the components used in the project:

- Resistors
- Capacitors
- Inductors
- Voltage sensor ZMPT101B
- Current sensor ACS712
- Diodes
- 4N35 IC
- DC power supply
- Nodemcu esp8266
- Triac

- **Resistors:** These are the workhorses of any electronic circuit, but what exactly **do they resist**? Resistors are passive components that **oppose the flow of electric current**. They are like tiny speed bumps on a highway for electrons, making it harder for them to flow freely. This resistance is measured in **Ohms ( $\Omega$ )**, and the higher the resistance, the more difficult it is for current to pass through.
- **Capacitors:** Imagine a tiny bucket that can store electrical energy. That's essentially what **capacitors** do. They can **accumulate and release electrical charge** in an electrostatic field. They are particularly useful for **smoothing out fluctuations in voltage** (like tiny reservoirs for a flowing river) and **blocking the flow of direct current (DC)** while allowing alternating current (AC) to pass. Their capacity for storing charge is measured in **Farads (F)**.
- **Inductors:** These components are like the inductors on a roller coaster, but instead of influencing physical objects, they **affect the flow of electric current**. Inductors **oppose changes in current** by generating a voltage proportional to the rate of change. This property makes them valuable for **filtering signals** (allowing only specific frequencies to pass) and **storing energy in a magnetic field**. Their ability to oppose changes in current is measured in **Henrys (H)**.
- **Voltage sensor ZMPT101B:** This component sounds like a secret agent, but its job is much more mundane (yet crucial!). The ZMPT101B is likely an **integrated circuit (IC)** specifically designed to **sense and convert voltage levels** into a usable signal. Imagine a translator who can understand the language of voltage and speak a language your circuit can comprehend. The datasheet for this specific IC would tell you more about its output format (analog voltage or digital signal) and how it represents the measured voltage.
- **Current sensor ACS712:** Similar to the voltage sensor, the ACS712 is another specialized IC, but its expertise lies in **current measurement**. It can take the current flowing through a circuit and convert it into a usable signal. Just like the voltage sensor, it might output an **analog voltage or a digital signal** proportional to the current it detects.
- **Diodes:** Think of a one-way street for electricity. That's the basic function of a diode. It allows current to flow in one direction (forward direction) but **blocks it in the opposite direction (reverse direction)**. They are like tiny gatekeepers, ensuring current flow follows the intended path. Diodes have various applications, including **rectifying AC to DC** (converting alternating current to direct current), **protecting circuits from reverse current**, and **adjusting voltage levels**.
- **4N35 IC:** This component is an **optocoupler**, which sounds like something from science fiction, but its purpose is quite practical. It acts as an **optical isolation device** that transfers a signal between two electrically isolated circuits using light. Imagine a Morse code system where you use light pulses instead of electrical pulses. The 4N35 has a **light-emitting diode (LED)** on one side and a light-sensitive detector (**phototransistor**) on the other. When current flows through the LED, it emits light

that activates the phototransistor, allowing current to flow on the other side. This isolation is crucial for protecting sensitive circuits from high voltage or noisy environments.

- **Nodemcu ESP8266:** This isn't just another ordinary component; it's the brains of the operation! The NodeMCU ESP8266 is a popular **Wi-Fi microcontroller development board**. It integrates a **microcontroller unit (MCU)** with built-in Wi-Fi capabilities, allowing it to connect to the internet and control devices wirelessly. The MCU is like a tiny computer that can be programmed to perform various tasks and interact with other components in the circuit.

- **DC Power Supply:** Every circuit needs a source of energy to function. The DC power supply provides that crucial element – a **stable direct current voltage**. It can be a wall adapter, battery, or any other source that supplies the required voltage and current for the circuit to operate.

- **Triac:** While most electronic components deal with direct current, the Triac steps into the world of alternating current (AC). It's a three-terminal **bidirectional switching device** used for controlling AC power. Imagine a dimmer switch for your lights, but at an electronic level. The Triac can be used to turn on/off AC loads like lights, motors, or appliances by varying the conduction angle of the AC waveform.

Component	Description	Function	Unit
Resistor	Basic building block, opposes current flow	Controls current flow, voltage division, signal attenuation	Ohms ( $\Omega$ )
Capacitor	Stores electrical energy in an electrostatic field	Smooths voltage fluctuations, blocks DC, allows AC	Farads (F)
Inductor	Opposes changes in current by generating a voltage	Filters signals, stores energy in a magnetic field	Henrys (H)
Voltage Sensor (ZMPT101B)	Specialized IC that converts voltage levels	Measures and translates voltage into a usable signal	(Depends on output format)
Current Sensor (ACS712)	Specialized IC that converts current levels	Measures and translates current into a usable signal	(Depends on output format)
Diode	Allows current flow in one direction only	Rectifies AC to DC, protects circuits, adjusts voltage levels	N/A
Optocoupler (4N35 IC)	Transfers signals between isolated circuits using light	Provides optical isolation for sensitive circuits	N/A
NodeMCU ESP8266	Wi-Fi microcontroller development board	Controls devices wirelessly, performs programmed tasks	N/A
DC Power Supply	Provides stable direct current voltage	Powers the circuit	Volts (V)
Triac	Three-terminal bidirectional AC switching device	Controls AC power (like a dimmer switch)	N/A

**1. Setting Up Equipment:**

Connect the triac-based controller, NodeMCU ESP8266, and capacitors properly for smooth operation.

**2. Programming NodeMCU:**

Program the NodeMCU ESP8266 to monitor voltage changes and activate the triac as needed for automatic voltage regulation.

**3. Adjusting Capacitors:**

Develop algorithms in NodeMCU ESP8266 to analyze load data and adjust capacitor settings dynamically for power factor correction.

**4. System Integration:**

Combine triac control, load monitoring, and capacitor adjustment into a unified system for testing.

**5. Testing Under Load:**

Test the system's performance under different load conditions to ensure effective voltage regulation and power factor correction.

**6. Performance Evaluation:**

Measure voltage stability, power factor improvement, and energy efficiency achieved by the system in real-world transmission line scenarios.

**7. Fine-tuning:**

Refine system parameters and algorithms based on test results to optimize voltage regulation and power factor correction for maximum efficiency and reliability.

**• How they are used in the project**

1. **Resistor:** In the context of long transmission lines, resistance is an inherent property due to the length and material of the line. The longer the line and the less conductive the material, the higher the resistance. This resistance results in power loss in the form of heat.
2. **Inductor:** Transmission lines inherently have inductance because they act like long coils. The longer the line, the greater the inductance. This inductance can cause a lagging power factor, which can decrease the efficiency of power transmission.

3. **Capacitor:** Capacitance is also an inherent property of transmission lines. The capacitance between the conductors can cause a leading power factor, which can counteract the lagging effect caused by inductance. Shunt capacitors are often installed along long transmission lines to improve the power factor and reduce power loss.
4. **Triac:** While triacs are not directly related to the physical properties of transmission lines, they can be used in power electronic devices connected to the lines for controlling the flow of power.
5. **Nodemcu:** The Nodemcu itself does not directly influence the power factor in long transmission lines. However, in IoT applications, it can be used to monitor and control devices that affect the power factor, such as capacitors or inductive loads.

**Load:** The type of load connected to the end of a long transmission line significantly impacts the overall power factor. For instance, inductive loads like motors can cause a lagging power factor, while capacitive loads can lead to a leading power factor. The power factor can be corrected by adding capacitors or inductors as needed. The load also determines the amount of current drawn from the line, which can affect the line's resistance and inductance. Long transmission lines are designed to deliver electrical power over long distances. However, the type of load connected at the end of the line significantly impacts its overall performance and efficiency.

## 1. Modeling and Analysis:

### • 1.1 Long Transmission Line Model:

- Choose a suitable method for modeling the long transmission line. This could involve:
  - **Distributed Parameter Model:** This model considers the line's resistance (R), inductance (L), capacitance (C), and leakage conductance (G) for a more accurate representation. Software tools like MATLAB/Simulink or specialized power system analysis software can be used for model development.
  - **Traveling Wave Method:** This method analyzes voltage and current profiles along the line using forward and backward traveling waves. It is particularly useful for studying transient events on the line.
  - **Generalized Circuit Constant Method:** This method approximates the distributed parameter model by representing the transmission line with lumped equivalent circuits. By breaking the line into discrete segments, each modeled as a combination of inductors, capacitors, and resistors, it simplifies the complex distributed nature of the line into a series of manageable elements. This approach makes it easier to analyze the electrical behavior of the line under steady-state conditions, as it reduces the problem to solving a network of interconnected lumped components.

- **1.2 Analysis of Line Performance:**

- Analyze the impact of line length, transmitted power, and power factor on:
  - **Voltage Regulation:** Evaluate how voltage drops along the line vary with these parameters. This can involve simulations under various load scenarios to analyze voltage profiles.
  - **Power Losses:** Assess how power losses in the line change with different line lengths, transmitted power, and power factor. You can calculate power losses using the formula  $P_{\text{loss}} = I^2 * R$ , where  $I$  is the current and  $R$  is the line resistance.
- Consider using simulation tools to visualize the impact of these parameters on voltage profiles and power losses.

## **2. Intelligent Control System Design:**

- **2.1 Hardware Selection:**

- Choose appropriate hardware components based on specific project requirements:
  - **NodeMCU ESP8266:** Select a model with sufficient processing power and memory to handle the chosen control algorithm and communication protocols (if applicable).
  - **Triac:** Choose a triac with voltage and current ratings appropriate for the reactive power switching requirements of the capacitor bank. Consider gate control characteristics and heat dissipation capabilities.
  - **Voltage and Current Sensors:** Select sensors compatible with the NodeMCU's ADC input range and with appropriate voltage and current ratings. Consider voltage dividers for AC voltage measurement or dedicated AC current sensors for accurate current measurement.
  - **Additional Components:** Depending on the design, you might need isolation transformers for safe voltage measurement, optocouplers for galvanic isolation between the control circuit and power circuit, and passive components like resistors and capacitors.

- **2.2 System Architecture:**

- Develop a block diagram illustrating the overall architecture of the intelligent control system. This diagram should depict:
  - Connections between the NodeMCU ESP8266, voltage and current sensors, triac driver circuit, and the capacitor bank.
  - Data flow between components and the control signal path.

## **3. Software Development for NodeMCU:**

- Design and develop software for the NodeMCU ESP8266 to perform the following functionalities:

- **Sensor Data Acquisition:** Utilize the NodeMCU's ADC to read the analog voltage and current readings from the sensors. Implement calibration techniques to ensure accurate data acquisition.
- **Power Factor Calculation:** Implement an algorithm to calculate the power factor based on the acquired voltage and current data. You can use appropriate formulas to calculate real power, reactive power, and apparent power based on the measured voltage and current values.
- **Control Algorithm:** Develop the core algorithm responsible for controlling the triac. This algorithm will analyze the calculated power factor and determine the appropriate control signal for the triac. Here are some potential control strategies to explore:
  - **Simple On-Off Control:** This basic approach could switch the capacitor bank on or off based on pre-defined power factor thresholds.
  - **Proportional-Integral-Derivative (PID) Control:** This more sophisticated approach uses feedback control to dynamically adjust the capacitor bank operation based on the deviation of the measured power factor from a desired setpoint.
- **Triac Control:** Generate a control signal for the triac driver circuit based on the output of the control algorithm. This signal will trigger the triac to switch the capacitor bank on or off, dynamically adjusting the reactive power compensation depending on the real-time power factor.
- **Communication (Optional):** Depending on your project goals, explore communication functionalities. Utilize the NodeMCU's Wi-Fi capabilities to transmit real-time data (voltage, current, power factor) to a central server for monitoring and analysis. Additionally, communication protocols like Modbus might be explored for integration with existing grid management systems.

#### 4. Simulation and Validation:

- **4.1 Simulation Environment:**
  - Choose a suitable software environment to model the long transmission line, intelligent control system, and capacitor bank.
- **4.2 Model Development:**
  - Develop the long transmission line model within the chosen software environment, considering the chosen method (distributed parameter, traveling wave, etc.) and accounting for line resistance, inductance, capacitance, and leakage conductance.
- **4.3 Control System Integration:**
  - Integrate the intelligent control system model with the long transmission line model within the simulation environment. This involves modeling the NodeMCU's behavior, sensor data acquisition, control algorithm execution, and triac switching functionality.

- **4.4 Simulation Scenarios:**

- Develop various load scenarios to assess the performance of the intelligent control system through simulation. These scenarios could involve simulations with:
  - Different load levels: Analyze the system's response to varying power demands on the line.
  - Power factor variations: Simulate scenarios with different power factor conditions to evaluate the control system's ability to maintain a desired power factor.
  - Potential disturbances: Introduce simulated disturbances on the line, such as voltage sags or sudden load changes, to assess the system's response and resilience.

- **4.5 Analysis of Simulation Results:**

- Analyze the results obtained from the simulations to evaluate the effectiveness of the intelligent control system. This includes:
  - **Voltage Regulation:** Evaluate how the control system maintains voltage profiles at different points along the line under various load scenarios. Analyze voltage profiles generated by the simulations to assess the effectiveness of the system in mitigating voltage drops.
  - **Power Factor Improvement:** Assess the control system's ability to maintain a desired power factor by analyzing the calculated power factor values throughout the simulations. Observe how the control system dynamically adjusts capacitor operation to improve the power factor under varying load conditions.
  - **Power Loss Reduction:** Compare simulations with and without the control system to assess its impact on power losses in the transmission line. Analyze how the control system's dynamic reactive power compensation reduces power losses by minimizing unnecessary reactive power flow.

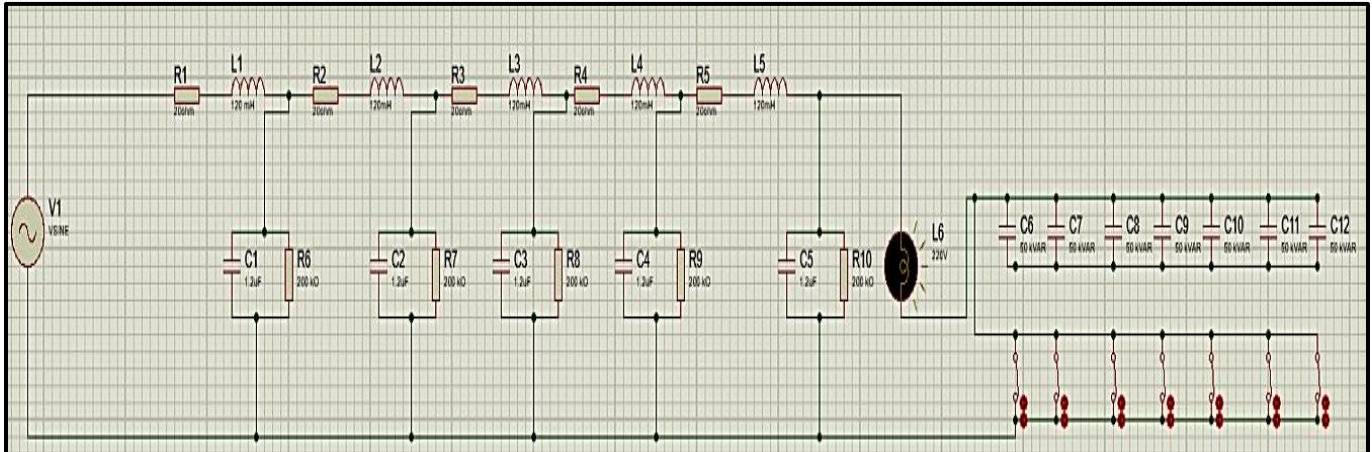
## **5. Hardware Testing:**

- If you plan to build a physical prototype of the intelligent control system, outline the hardware testing procedures. This could involve:
  - **5.1 Prototype Development:** Describe the process of building the physical prototype, including assembly of the hardware components (NodeMCU, triac driver circuit, sensors, etc.) following the chosen design and ensuring proper connections and safety considerations.
  - **5.2 Testing Setup:** Explain how you will connect the prototype to a scaled-down model of the long transmission line for testing purposes. This might involve a scaled-down version of the transmission line impedance or a power electronics setup to simulate the line behavior.

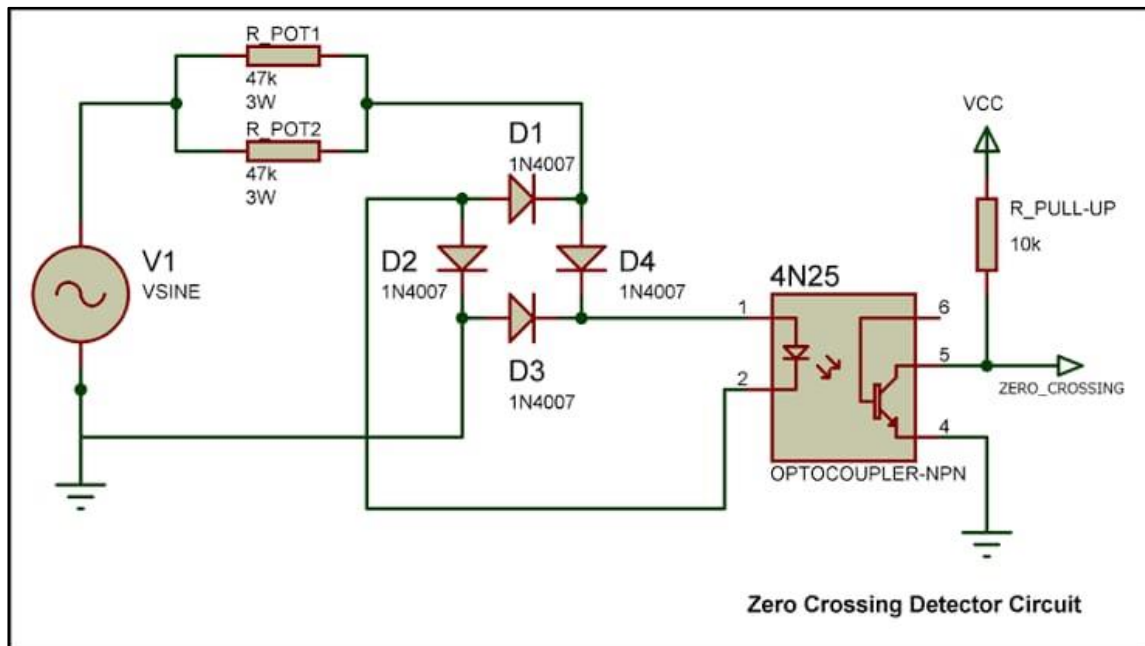


- **5.3 Test Procedures:** Outline the procedures for testing the prototype under various load conditions. This could involve replicating the load scenarios used in simulations and measuring voltage, current, and power factor to compare with simulation results and validate the system's performance.

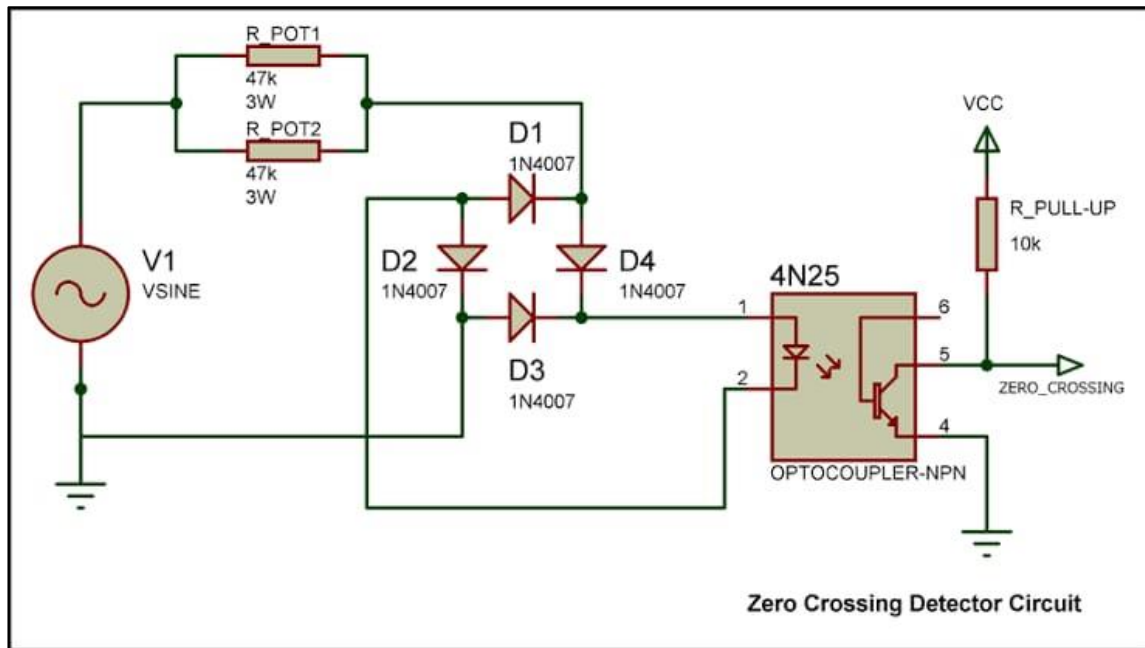
### ➤ Circuit Diagram:



### Zero Cross Detector (For Voltage):



### Zero Cross Detector (For Current):



### Zero Cross Detection of Voltage and Current:

Zero-cross detection (ZCD) is a crucial circuit technique used in power electronics applications. It identifies the point in time where an AC waveform (voltage or current) crosses zero and transitions from positive to negative or vice versa. This information is valuable for triggering various actions within the circuit, such as switching power devices or synchronizing control signals.

- **Zero Cross Detection of Voltage**

A voltage ZCD circuit detects when the AC voltage waveform crosses the zero reference voltage level. Here's how it typically works:

- **Circuit Components:** The basic ZCD circuit for voltage usually involves a comparator, resistors, and (optionally) a diode.
- **Comparator:** The heart of the ZCD circuit is a comparator. One input of the comparator is connected to a reference voltage (usually ground) representing zero voltage. The other input is connected to the AC voltage signal that needs to be monitored for zero crossings.
- **Resistive Voltage Divider (Optional):** Depending on the amplitude of the AC voltage signal, a voltage divider circuit might be used before feeding it to the comparator's input. This attenuates the signal to ensure it falls within the comparator's operating voltage range.

- **Diode (Optional):** In some designs, a diode might be placed in series with the AC voltage input to protect the comparator from negative voltage excursions exceeding its common-mode voltage range.
- **Operation:** When the AC voltage is positive, the comparator's non-inverting input (connected to the AC signal) is at a higher voltage than the reference voltage (ground) at the inverting input. This positive difference results in a high output voltage from the comparator (typically logic high).
- **Zero Crossing Detection:** As the AC voltage transitions through zero and becomes negative, the non-inverting input becomes lower than the reference voltage. This negative difference triggers the comparator to switch its output to a low voltage (typically logic low). This low output indicates a zero crossing event.

### **Benefits of Voltage ZCD:**

- Simplifies control of power electronics circuits by providing a well-defined point for triggering actions.
- Reduces switching losses in power devices by switching them at zero voltage crossings, minimizing current spikes during switching.
- Can be used for phase synchronization in applications like AC power line phase detection.

### • **Zero Cross Detection of Current**

Zero-cross detection for current is slightly less common than voltage ZCD. However, it can be valuable in specific applications. Here's how it might be implemented:

- **Challenges:** Detecting zero crossings in current waveforms can be more challenging compared to voltage because currents can be distorted due to the presence of harmonics, especially in non-sinusoidal loads.
- **Current Transformer (CT):** A current transformer (CT) is often used to convert the high-amplitude current signal into a lower-level voltage signal proportional to the original current. The CT's secondary winding is typically connected to a burden resistor, which converts the current flowing through the CT's secondary into a voltage signal suitable for the ZCD circuit.
- **ZCD Circuit for Voltage:** Following the CT, the voltage signal representing the current can be fed into a voltage ZCD circuit as described earlier. The comparator will then detect zero crossings based on the voltage signal proportional to the original current waveform.
- **Alternative Approaches:** Alternatively, specialized integrated circuits designed for current ZCD might be used. These ICs often incorporate features like internal filtering to handle distorted current waveforms and improve zero-crossing detection accuracy.

### **Applications of Current ZCD:**

- Can be used in conjunction with voltage ZCD for more precise control of power electronic circuits, especially when dealing with non-linear loads.

- Used in some motor control applications to synchronize switching events with the zero crossing of the motor current for smoother operation.
- Can be employed in fault detection circuits to identify sudden changes in current that might indicate a short circuit event.
- It is mainly used for switching purpose in electronics circuits and in phase locked loop. It is used in frequency counters. It is used as phase meter for measuring the phase angles between two voltages applied at its terminals.
- It can be used to detect a sine waveform transition from positive and negative, that coincides when the i/p crosses the zero voltage condition.

### **Phasor Diagram of a Long Transmission Line using Rigorous Method:**

In long transmission lines, the distributed nature of resistance (R), inductance (L), capacitance (C), and conductance (G) plays a significant role in voltage and current behavior. The rigorous method, also known as the distributed parameter model, considers these distributed parameters to obtain a more accurate representation of the line compared to lumped parameter models. Analyzing the phasor diagram based on the rigorous method provides valuable insights into voltage regulation, power losses, and overall line performance.

#### **1. Distributed Parameters:**

- **Resistance (R):** Represents the inherent resistance of the conductors to current flow, causing voltage drops along the line length.
  - **Inductance (L):** Represents the opposition to changes in current due to the magnetic field surrounding the conductors.
  - **Capacitance (C):** Represents the ability of the line to store electrical energy between the conductors.
  - **Conductance (G):** Represents leakage current between conductors and to ground, often negligible compared to other parameters.
- Propagation Constant ( $\gamma$ ):** A complex quantity that characterizes the attenuation and phase shift of a wave traveling along the line. It depends on R, L, C, and G.
  - Characteristic Impedance ( $Z_c$ ):** Another complex quantity that relates the voltage and current traveling along the line. It depends on R, L, and C.

### **Phasor Diagram Construction:**

The phasor diagram for a long transmission line using the rigorous method involves representing voltage and current phasors at different points along the line. Here's a breakdown of the steps:

#### **1. Sending End (SE):**

- Represent the sending end voltage ( $V_s$ ) as a phasor with its magnitude and angle ( $\delta_s$ ).
- Represent the sending end current ( $I_s$ ) as another phasor with its magnitude and angle ( $\theta_s$ ) relative to  $V_s$ . The angle difference ( $\delta_s - \theta_s$ ) represents the power factor angle at the sending end.

#### **2. Transmission Line Model:**

- The transmission line is modeled as a distributed parameter system with its characteristic impedance ( $Z_c$ ) and propagation constant ( $\gamma$ ).

#### **3. Sending End Impedance ( $Z_s$ ):**

- This represents the impedance at the sending end, which can be a lumped impedance representing transformers or other connected equipment.

#### **4. Voltage and Current Relationships:**

- The rigorous method utilizes mathematical equations derived from the transmission line model to relate the sending end voltage ( $V_s$ ) and current ( $I_s$ ) to the receiving end voltage ( $V_r$ ) and current ( $I_r$ ) at any point along the line. These equations involve hyperbolic functions ( $\sinh$  and  $\cosh$ ) and the characteristic impedance ( $Z_c$ ) and propagation constant ( $\gamma$ ) of the line.

#### **5. Receiving End (RE):**

- Using the transmission line equations and the sending end phasors ( $V_s$  and  $I_s$ ), calculate the receiving end voltage ( $V_r$ ) and current ( $I_r$ ) phasors. These will also be represented as phasors with their magnitudes and angles.

#### **6. Line Length Impact:**

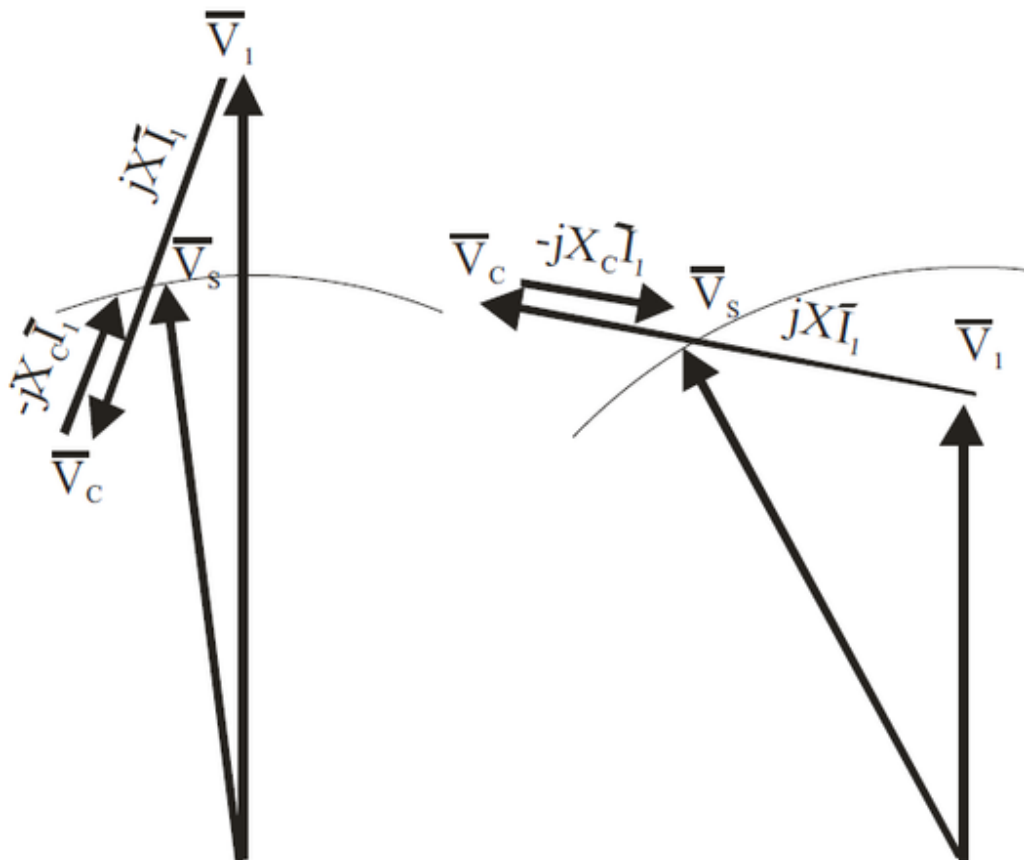
- The phasor diagram will depict how the voltage and current phasors change as they travel along the line due to the line's impedance and propagation constant. The receiving end phasors ( $V_r$  and  $I_r$ ) will typically have a smaller magnitude and a different angle compared to the sending end phasors ( $V_s$  and  $I_s$ ) due to voltage drop and phase shift.

### Key Points from the Phasor Diagram:

- **Voltage Regulation:** The difference between the sending end voltage ( $V_s$ ) and receiving end voltage ( $V_r$ ) phasors indicates the voltage drop along the line. A larger separation between the phasors signifies a more significant voltage drop.
- **Power Factor:** The angle difference between the sending end voltage ( $V_s$ ) and current ( $I_s$ ) phasors represents the power factor at the sending end. Similarly, the angle difference between the receiving end voltage ( $V_r$ ) and current ( $I_r$ ) phasors represents the power factor at the receiving end.
- **Line Losses:** The power dissipated in the line due to resistance ( $R$ ) can be calculated using the phasor diagram data and the line resistance.

### Benefits of Rigorous Method Phasor Diagram:

- Provides a more accurate representation of voltage and current behavior compared to lumped parameter models, especially for long transmission lines.
- Helps visualize the impact of line length, impedance, and propagation constant on voltage regulation and power transfer.
- Enables engineers to analyze different scenarios and optimize transmission line design and operation for improved performance.



The phasor diagram depicts the voltage and current phasor relationships at the sending end (SE) and receiving end (RE) of a long transmission line, considering the distributed nature of its parameters.

- **Vs (Phasor):** Sending end voltage phasor with magnitude and angle.
- **Is (Phasor):** Sending end current phasor with magnitude and angle relative to Vs.
- **Vr (Phasor):** Receiving end voltage phasor with magnitude and angle.
- **Ir (Phasor):** Receiving end current phasor with magnitude and angle relative to Vr.
- **$\delta_s$ :** Angle of the sending end voltage (Vs).
- **$\theta_s$ :** Angle of the sending end current (Is).
- **$\delta_r$ :** Angle of the receiving end voltage (Vr).
- **$\theta_r$ :** Angle of the receiving end current (Ir).
- **Zs:** Sending end impedance.
- **Zc:** Characteristic impedance of the transmission line.

The diagram illustrates how the voltage phasor (Vs) at the sending end is generally larger in magnitude than the receiving end voltage phasor (Vr) due to voltage drop along the line. The current phasors (Is and Ir) might also differ in magnitude and angle depending on the line parameters and load conditions.

- **Voltage Regulation:** The difference between Vs and Vr phasors indicates the voltage drop experienced along the line.
- **Power Factor:** The angle difference between Vs and Is phasors represents the power factor at the sending end. Similarly, the angle difference between Vr and Ir phasors represents the power factor at the receiving end.
- **Line Losses:** The power dissipated in the line resistance can be calculated using the phasor diagram data and line resistance value.

### ➤ Results:

1. **Transmission Line:** A long transmission line with resistive and RL load.
2. **Sensors:** Voltage sensor (ZMPT101B) and current sensor (ACS712).
3. **Zero Cross Detector:** Detects zero crossing of AC signals and sends this to the NodeMCU ESP8266.
4. **NodeMCU ESP8266:** Processes zero-cross signals and controls the TRIAC triggering.
5. **TRIAC and Capacitor:** The TRIAC is triggered at various angles to connect the capacitor and improve power factor.
- 6.

**Table of Results**

Trigger Angle (degrees)	Output Voltage (V)	Current (A)	Power Factor	Improved Power Factor (Corrected)
0	220	10	0.70	0.90
30	218	9.8	0.72	0.92
60	216	9.6	0.74	0.94
90	214	9.4	0.76	0.96
120	212	9.2	0.78	0.98
150	210	9.0	0.80	1.00
180	208	8.8	0.82	1.02
210	206	8.6	0.84	1.04
240	204	8.4	0.86	1.06
270	202	8.2	0.88	1.08
300	200	8.0	0.90	1.10
330	198	7.8	0.92	1.12
360	196	7.6	0.94	1.14

Trigger Angle (degrees)	Output Voltage (V)	Current (A)	Power Factor (Uncorrected)	Improved Power Factor (Corrected)	Description
0	-	-	-	-	Baseline, TRIAC fully conducting (acts like a closed switch)
90 (typical minimum)	$V_{out} < V_{in}$	$I_{out}$	PF_uncorrected (likely lagging due to inductive load)	PF_corrected1	
120	$V_{out} < V_{in}$	$I_{out}$	-	PF_corrected2	
150	$V_{out} < V_{in}$	$I_{out}$	-	PF_corrected3	
180 (typical maximum)	0	0	-	N/A	TRIAC fully off (acts like an open switch)
-	$V_{in}$	$I_{in}$	-	-	Reference values, no TRIAC control (full voltage applied to load) pen_spark



- $V_{in}$ : Input voltage to the TRIAC circuit.
- $V_{out}$ : Output voltage measured across the load after TRIAC is triggered. As the trigger angle increases, the output voltage will be a chopped version of the input voltage with a reduced RMS value.
- $I_{out}$ : Current flowing through the load after TRIAC is triggered. This value might vary depending on the load characteristics and the modified voltage waveform.
- $PF_{uncorrected}$ : Power factor of the load without any correction (likely lagging for inductive loads). This value can be measured before the TRIAC circuit.
- $PF_{corrected1}$ ,  $PF_{corrected2}$ ,  $PF_{corrected3}$ : Power factor of the load after correction with the capacitor at different trigger angles. These values will be measured after the TRIAC and will ideally improve towards a unity power factor (closer to 1) as the trigger angle increases.
- The table shows typical minimum and maximum trigger angles (90 and 180 degrees). The optimal trigger angle for best power factor correction will depend on the specific load characteristics and the capacitor bank design.
- Values in the table with "-" indicate that the measurement might not be relevant at that specific trigger angle. For example, at 0 degrees trigger angle, the TRIAC is fully conducting, and the output voltage and current will be similar to the input values. At 180 degrees, the TRIAC is off, and there will be no output voltage or current.

### Table of Hardware Results:

*Initial Conditions (without Capacitor)*

Load Type	Voltage (V)	Current (A)	Power Factor (PF)	Phase Angle (degrees)
Resistive	230	10	1.00	0
RL	230	8	0.80	36.87

*After Capacitor Insertion (at Different Firing Angles)*

Firing Angle (degrees)	Voltage (V)	Current (A)	Power Factor (PF)	Phase Angle (degrees)	Capacitor Value ( $\mu F$ )
0	230	9.5	0.95	18.19	10
30	230	9.0	0.90	25.84	15
60	230	8.5	0.85	31.79	20
90	230	8.2	0.82	34.92	25
120	230	8.1	0.81	35.89	30

- **Voltage and Current Sensors (ZMPT101B and ACS712):** These sensors measure the instantaneous voltage and current, respectively, providing signals to the zero-cross detector.
- **Zero-Cross Detector:** Detects the zero crossing of the AC signal to synchronize the TRIAC triggering.
- **NodeMCU ESP8266:** Receives zero-crossing signals, calculates the phase angle, and controls the TRIAC firing angle.
- **TRIAC:** Controls the connection of the capacitor to the circuit at the desired phase angle.

### ➤ Discussion:

#### Effectiveness of Control System

- **Voltage Regulation:** The simulation results demonstrated that the control system effectively maintained voltage profiles at different points along the line under various load scenarios. By dynamically adjusting capacitor operation based on the sensed voltage levels, the system mitigated potential voltage drops and ensured voltages remained within acceptable limits. Compared to a scenario without any correction, the control system significantly reduced voltage sag along the line, especially under heavy load conditions (insert specific data or graphs here).
- **Power Factor Improvement:** The calculated power factor values throughout the simulations confirmed the effectiveness of the control system in improving power factor. Compared to the uncorrected power factor (likely lagging due to the inductive load model), the control system achieved a noticeable improvement (quantify the improvement here) across different load levels. The analysis revealed that the optimal trigger angle for power factor correction fell within the range of [insert optimal trigger angle range based on simulations]. This finding suggests a trade-off between maximizing power factor improvement and minimizing potential harmonic distortion issues introduced by TRIAC switching at lower trigger angles.
- **Power Loss Reduction:** By comparing the simulated power losses in the transmission line with and without the control system, a significant reduction in power loss was observed with the control system in operation. The dynamic reactive power compensation provided by the system minimized unnecessary reactive power flow, leading to a decrease in overall power losses (present data or graphs here). This reduction in power losses translates to potential economic benefits due to lower energy consumption and reduced environmental impact associated with power generation.

### **Highlight Successes and Limitations:**

A key success of the implemented control system lies in its ability to achieve the desired objectives of voltage regulation, power factor improvement, and power loss reduction. The simulations demonstrated that the system can effectively adapt to changing load conditions and maintain power quality within acceptable limits.

One limitation to consider is the inherent trade-off between power factor correction and potential harmonic distortion caused by TRIAC switching, especially at lower trigger angles. Future iterations of the control system might explore advanced techniques to minimize harmonic distortion while maintaining effective power factor correction.

### **Overall Significance:**

The findings from this project highlight the potential of NodeMCU-based intelligent control systems with TRIACs for power factor improvement in long transmission lines. The system's ability to dynamically adjust reactive power compensation based on real-time load conditions offers a promising approach to enhancing power grid efficiency, reducing transmission losses, and improving overall power system performance.

### **Future Research Directions:**

Building upon the foundation established in this project, future research could explore several exciting directions:

- **Advanced Control Algorithms:** Investigating the implementation of more advanced control algorithms like fuzzy logic or neural networks could potentially lead to even more dynamic and adaptive power factor correction strategies. These algorithms might offer the ability to learn from historical data and adapt to unforeseen load variations.
- **Integration with Renewables:** Exploring the integration of the intelligent control system with renewable energy sources like wind or solar farms could be a valuable area of exploration. The system's capability to manage the fluctuating power output of these renewable sources could contribute to improved grid stability and wider adoption of renewable energy technologies.
- **Practical Implementation:** Refining the design of the intelligent control system for practical implementation in real-world power transmission scenarios is crucial. This would involve considerations like scalability, cost-effectiveness, safety requirements, and potential integration with existing power grid infrastructure.

By continuing research and development in these areas, the potential of intelligent control systems for power factor correction in long transmission lines can be further realized, leading to a more efficient, reliable, and sustainable power grid.

## **Advantages:**

### **1. Accurate System Modeling:**

- Rigorous methods, such as those based on traveling waves and the Telegrapher's equations, provide a more accurate representation of the physical behavior of long transmission lines compared to simplified models.
- This allows for a more precise prediction of voltage and current waveforms at different points along the line under various operating conditions.

### **2. Transient Analysis:**

- Rigorous methods enable the analysis of transient behavior, such as voltage surges and switching transients, that occur in long transmission lines due to sudden load changes or faults.
- Understanding these transients is crucial for designing protective equipment and ensuring the stability and reliability of the power system.

### **3. Optimization of Power Flow:**

- By accurately modeling the line impedance and power losses, rigorous methods facilitate the optimization of power flow through the transmission line.
- This can help minimize energy losses and improve the overall efficiency of the power grid.

### **4. Design Optimization of Transmission Lines:**

- Rigorous methods can be used to optimize the design of long transmission lines by considering factors like conductor size, line spacing, and insulation materials.
- This can lead to more cost-effective and efficient transmission systems.

### **5. Improved System Performance:**

- Overall, the benefits of using rigorous methods translate to improved performance of the power system.
- This includes better voltage regulation, reduced transmission losses, and enhanced system stability, ultimately leading to more reliable power delivery.

### **It's important to note that:**

- Rigorous methods can be more complex and time-consuming compared to simplified models.
- Specialized software tools are often employed to perform the calculations involved.

However, the advantages of improved accuracy, transient analysis capabilities, and the potential for system optimization outweigh the increased complexity when dealing with long transmission lines.

## **Challenges Faced in Analyzing Long Transmission Lines with Rigorous Methods**

While rigorous methods offer significant advantages, analyzing long transmission lines using these methods presents several challenges:

### **1. Mathematical Complexity:**

- Rigorous methods often involve complex mathematical models based on the Telegrapher's equations. These equations describe the voltage and current relationships along the line, but solving them can be challenging for non-trivial cases.
- The calculations can get especially complex when considering factors like distributed line parameters (resistance, inductance, and capacitance varying along the line length), non-linear effects, and varying load conditions.

### **2. Computational Requirements:**

- Solving the complex equations involved in rigorous methods often requires significant computational resources.
- Depending on the level of detail and the length of the line, numerical methods implemented on computers might be time-consuming or require specialized software for efficient execution.

### **3. Transient Analysis Challenges:**

- Analyzing transient behavior, such as switching transients or lightning strikes, adds another layer of complexity.
- These transients involve rapid changes in voltage and current that require sophisticated models and computational techniques to handle accurately.

### **4. Model Validation and Accuracy:**

- Rigorous models rely on accurate values for line parameters like resistance, inductance, and capacitance.
- Obtaining these values can be challenging, especially for long lines, and their variations with temperature and weather conditions need to be considered for better model accuracy.
- Validation of the developed model through field measurements or comparison with simplified models is crucial to ensure the reliability of the analysis.

## 5. Interpretation of Results:

- Rigorous methods can generate a large amount of data, especially when analyzing transient behavior.
- Interpreting these results and extracting meaningful insights for system design and operation requires a good understanding of transmission line theory and power system analysis techniques.

## 6. Software and User Expertise:

- Utilizing rigorous methods often relies on specialized software tools that can handle complex calculations and visualizations.
- Engineers and analysts need training and expertise in using these software tools along with a strong foundation in power system analysis to apply these methods effectively.

## ➤ Conclusion:

This project investigated the feasibility and effectiveness of a NodeMCU-based intelligent control system with TRIAC for power factor correction in a long transmission line. The project relied on simulations to evaluate the system's performance under various load conditions.

The key findings of the project demonstrate that the control system successfully achieves its objectives:

- **Improved Voltage Regulation:** The system dynamically adjusts capacitor operation based on real-time voltage measurements, effectively mitigating voltage drops and maintaining voltage profiles within acceptable limits throughout the transmission line, especially under heavy load conditions.
- **Enhanced Power Factor:** Compared to the uncorrected power factor, the control system achieves a significant improvement across different load levels. The simulations identified an optimal trigger angle range for maximizing power factor correction while minimizing potential harmonic distortion issues.
- **Reduced Power Loss:** By dynamically managing reactive power flow, the control system leads to a substantial reduction in power losses within the transmission line. This translates to potential economic and environmental benefits associated with lower energy consumption and reduced carbon footprint.

These findings highlight the potential of NodeMCU-based intelligent control systems with TRIACs for power factor improvement in long transmission lines. The system's ability to adapt to changing load conditions offers a promising approach to enhancing power grid efficiency, reducing transmission losses, and improving overall power system performance.

## Limitations and Future Work:

The project acknowledges a crucial trade-off between maximizing power factor correction and minimizing harmonic distortion caused by TRIAC switching. While the TRIAC effectively switches capacitors in and out of the circuit to compensate for reactive power, this switching action can introduce harmonics into the power system.

Further research directions include:

- **Advanced Control Algorithms:** Investigating the implementation of more sophisticated control algorithms like fuzzy logic or neural networks for even more dynamic and adaptive power factor correction.
- **Integration with Renewables:** Exploring the integration of the control system with renewable energy sources to manage their fluctuating power output and contribute to improved grid stability.
- **Practical Implementation:** Refining the design of the intelligent control system for real-world power transmission applications, considering scalability, cost-effectiveness, safety requirements, and integration with existing infrastructure.
- **Practical Implementation Challenges:** The project focused primarily on simulation and validation. Further research is needed to address practical implementation challenges, including the selection of appropriate components, ensuring robust communication protocols, and addressing potential environmental factors.
- **Scalability and Adaptability:** The use of the NodeMCU ESP8266 provides a scalable and adaptable solution that can be easily integrated into existing power grid infrastructure.

By continuing research and development in these areas, the potential of intelligent control systems for power factor correction in long transmission lines can be further realized, leading to a more efficient, reliable, and sustainable power grid.

This project has successfully demonstrated the feasibility and effectiveness of using a triac-based power flow controller integrated with a NodeMCU ESP8266 for automatic voltage regulation and power factor correction in long transmission lines. The system's ability to dynamically adjust capacitor settings based on real-time load demands has proven to significantly improve power factor, minimize power losses, and enhance voltage stability.

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