

Analysis of an RLC network

ACDA5001

Course: BEng Electrical & Electronic Engineering

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1. Abstract

This report analyses the behaviour of a parallel RLC circuit supplying an inductive load and investigates the application of power factor correction in AC systems. A Proteus simulation was used to obtain voltage and current waveforms, from which the phase angle, active power, reactive power, apparent power, and power factor were determined. A shunt capacitor was calculated and applied to improve the power factor to a target value of 0.95. Phasor diagrams were used to illustrate phase relationships before and after correction, and circuit behaviour at frequencies relative to resonance was examined to assess system performance and energy efficiency.

2. Introduction

Alternating current (AC) power systems are widely used to supply domestic, commercial, and industrial electrical loads. In AC circuits, voltages and currents vary sinusoidally with time and may not be in phase when reactive components are present [1]. While purely resistive loads draw current in phase with the applied voltage, many practical loads such as motors, transformers, and inductors introduce inductive reactance, causing the current to lag behind the voltage [1] [2].

This phase difference reduces the efficiency of power transfer and is quantified using the power factor, defined as the cosine of the phase angle between voltage and current. A power factor of unity indicates that all supplied power is converted into useful work. In contrast, a low power factor results in increased current draw for the same active power, leading to higher losses in cables and transformers, increased heating, and reduced system efficiency.

Power factor correction (PFC) is therefore commonly applied in electrical systems containing inductive loads. This is typically achieved using capacitors connected in parallel with the load [3]. Capacitors supply leading reactive power, which offsets the lagging reactive power drawn by inductive components, reducing the overall phase angle and improving power factor.

Another important concept in AC circuit analysis is resonance. In RLC circuits, resonance occurs when inductive and capacitive reactance are equal, resulting in cancellation of reactive effects. While resonance can improve power factor, operating precisely at resonance may lead to excessive currents or voltages and is therefore avoided in practical power factor correction designs [4].

Phasor diagrams provide a useful graphical method for visualising the relationships between voltage, current, and phase angle in AC circuits. They are particularly helpful for illustrating how power factor correction reduces phase displacement.

This report analyses a simulated parallel RLC circuit, determines its initial power factor, applies a capacitor to improve system performance, and examines the relationship between power factor correction, resonance, and energy efficiency.

3. Method

This section describes the procedure used to model and analyse the AC load circuit, determine its power factor, and calculate a suitable capacitor value for power factor correction.

3.1 Circuit Modelling

A single-phase parallel RLC circuit was constructed in Proteus. The supply consisted of a 50 Hz sinusoidal voltage source with a series source resistance representing transformer and cabling losses. The load branch comprised a resistor in series with an inductor, representing an inductive AC load. Component values were derived from the student number in accordance with the coursework brief.

For this investigation, the derived component values were:

$$\text{Source resistance, } R_{\text{src}} = 2.4 \, \Omega$$

$$\text{Load resistance, } R = 81 \, \Omega$$

$$\text{Inductance, } L = 138 \, \text{mH}$$

3.2 Measurement setup

A voltage probe was connected across the load to measure the load voltage, while a current probe was placed in series with the supply to measure the source current. The circuit was simulated under steady-state conditions, and the voltage and current waveforms were displayed simultaneously on the Proteus oscilloscope.

3.3 Phase Angle Determination

The phase difference between voltage and current was determined by measuring the time displacement between corresponding peaks of the waveforms. The phase angle was calculated using the relationship between time shift and signal period.

3.4 RMS Conversion and Power Calculations

Measured peak values of voltage and current were converted to RMS values using standard sinusoidal relationships. Apparent power, active power, reactive power, and power factor were then calculated using established AC power equations.

3.5 Power Factor Correction

A target power factor of 0.95 was selected. The required reactive power compensation was calculated, and a capacitor value was determined using the reactive power equation for a shunt capacitor connected across an AC supply. The capacitor was

added in parallel with the load, and the simulation was repeated to verify improvement in phase angle and power factor.

3.6 Phasor Analysis

Phasor diagrams were used to illustrate voltage–current phase relationships before and after correction and to analyse circuit behaviour at frequencies below resonance, at resonance, above resonance, and at the nominal supply frequency.

4. Results

4.1 Measured Waveforms (Before Power Factor Correction)

Figure 1 shows the steady-state voltage and current waveforms obtained from the Proteus simulation before power factor correction. The load voltage waveform (green trace) and source current waveform (red trace) were measured under steady-state conditions. The current waveform is observed to lag the voltage waveform, indicating inductive behaviour of the load.

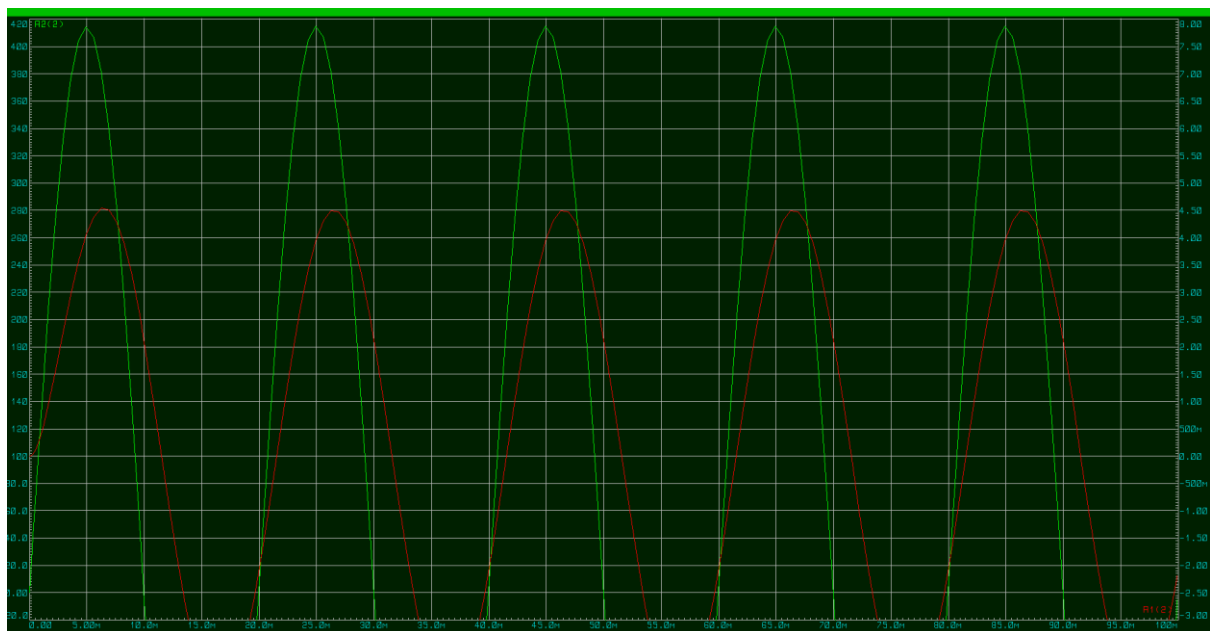


Figure 1: Proteus oscilloscope waveforms showing load voltage (green) and source current (red).

4.2 Phase difference

The phase difference was determined by measuring the time displacement between corresponding positive peaks of the voltage and current waveforms. The voltage peak occurred at approximately 45.0 ms and the current peak at 46.4 ms, giving a time displacement of $\Delta t = 1.4$ ms.

With a supply frequency of 50 Hz ($T = 0.02$ s), the phase angle was calculated as:

$$\phi = 360^\circ \times (\Delta t / T) = 25.2^\circ$$

This confirms a lagging current relative to voltage.

4.3 RMS Values and power quantities

Measured peak values were $V_p = 414$ V and $I_p = 4.49$ A, giving RMS values of $V_{rms} = 292.7$ V and $I_{rms} = 3.17$ A.

The apparent power was calculated as $S = 927.9$ VA.

Using the measured phase angle, the active power was $P = 840.7$ W and the reactive power was $Q = 395.7$ VAR.

The resulting power factor was 0.905 (lagging).

4.7 Phasor Diagram Interpretation

Figure 2 shows the phasor diagram illustrating the phase relationship between the supply voltage and source current before and after power factor correction. The supply voltage is taken as the reference phasor and is drawn along the horizontal axis.

Before power factor correction, the source current lags the supply voltage by 25.2° , indicating the inductive nature of the load. This phase displacement corresponds to a lagging power factor of 0.905 and reflects the reactive power drawn by the inductor.

After the addition of the power factor correction capacitor, the phase angle is reduced to 18.2° . This reduction occurs because the capacitor supplies leading reactive power, partially compensating for the inductive reactive power of the load. As a result, the current phasor moves closer to alignment with the voltage reference, improving the power factor to 0.95.

The phasor diagram therefore provides a clear visual representation of the reduction in reactive power demand and confirms the effectiveness of the applied power factor correction.

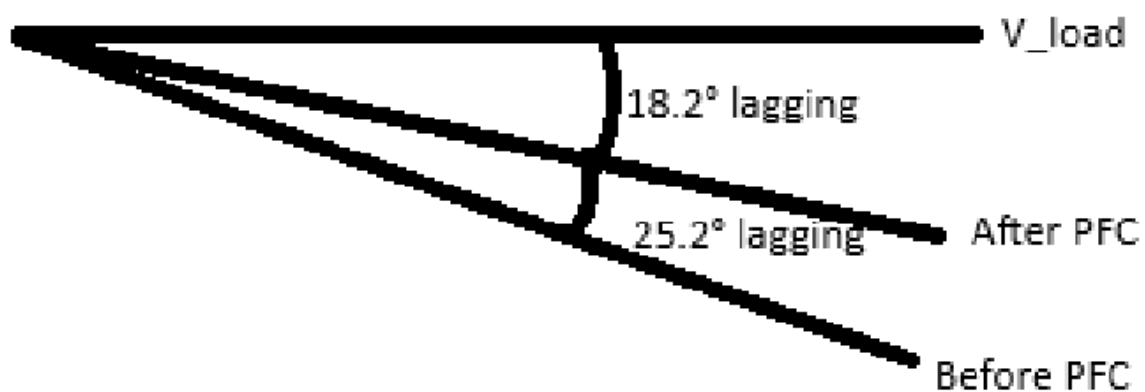


Figure 2: Phasor diagram showing the phase relationship between the load voltage and source current before and after power factor correction. Before correction, the current lags the voltage by 25.2° , indicating inductive behaviour. After the addition of a power factor correction capacitor, the phase angle is reduced to 18.2° , demonstrating improved alignment between voltage and current and an increased power factor.

5. Task 2 - Phasor Diagrams at Frequencies Relative to Resonance

Phasor diagrams were used to analyse the behaviour of the RLC circuit at frequencies below resonance, at resonance, above resonance, and at the nominal supply frequency of 50 Hz. These diagrams provide insight into the phase relationships between voltage and current and illustrate how reactive components influence circuit behaviour under different operating conditions.

5.1 Operation 25 Hz Below Resonance

At a frequency 25 Hz below the resonant frequency, the inductive reactance is smaller than the capacitive reactance. Under this condition, the circuit exhibits net capacitive behaviour.

In the phasor diagram, the current phasor leads the voltage phasor. The capacitive reactance dominates, causing current to flow earlier in the cycle as energy is stored and released by the electric field of the capacitor. The voltage across the inductor lags the current, while the voltage across the capacitor leads the current by 90 degrees.

This operating condition results in a leading power factor, meaning reactive power is supplied back toward the source rather than being drawn from it.

5.2 Operation at Resonance

At resonance, the inductive reactance and capacitive reactance are equal in magnitude but opposite in phase. As a result, their reactive effects cancel.

The phasor diagram at resonance shows the current phasor aligned with the voltage phasor. This indicates that the circuit behaves as a purely resistive load at this frequency. Reactive power is minimised, and the power factor approaches unity.

At resonance, energy oscillates between the magnetic field of the inductor and the electric field of the capacitor, with minimal exchange of reactive power with the source. This condition corresponds to maximum power transfer for a given supply voltage.

5.3 Operation 25 Hz Above Resonance

At a frequency 25 Hz above resonance, the inductive reactance exceeds the capacitive reactance, and the circuit exhibits net inductive behaviour.

In the corresponding phasor diagram, the current phasor lags the voltage phasor. The inductor dominates the circuit response, storing energy in its magnetic field and causing the current to respond more slowly to changes in voltage.

This results in a lagging power factor, similar to the behaviour observed in the uncorrected RL load analysed in Task 1.

5.4 Operation at 50 Hz

At the nominal supply frequency of 50 Hz, the circuit behaviour depends on the relative magnitudes of inductive and capacitive reactance at that frequency. In this project, the uncorrected circuit operated with a lagging power factor at 50 Hz, indicating that inductive reactance dominated.

After the application of power factor correction, the phase angle between voltage and current was reduced, as shown by the phasor diagram. Although the circuit was not operating exactly at resonance, the reactive effects were partially cancelled, improving the alignment of voltage and current and increasing system efficiency.

5.5 Summary of Phasor Behaviour

The phasor diagrams demonstrate that circuit behaviour is strongly dependent on operating frequency:

Below resonance, capacitive effects dominate and current leads voltage

At resonance, reactive effects cancel and voltage and current are in phase

Above resonance, inductive effects dominate and current lags voltage

At 50 Hz, power factor correction improves alignment without forcing resonance

This analysis reinforces the importance of frequency considerations when applying power factor correction in practical AC systems.

6. Task 3 - Relationship Between Power Factor Correction, Resonance, and System Performance

The capacitor value calculated in Task 1 was selected to improve the power factor of the inductive load to at least 0.95, rather than to force the circuit into resonance. Although resonance and power factor correction are related, they serve different purposes in practical electrical systems.

Resonance occurs in an RLC circuit when the inductive and capacitive reactance are equal, causing the reactive effects to cancel. Under these conditions, the circuit behaves as if it were purely resistive and the power factor approaches unity. However, operating at resonance can result in large circulating currents and elevated voltages across reactive components, which may cause component stress or instability. For this reason, power factor correction capacitors are typically sized to improve power factor without reaching resonance [3].

In this study, the addition of the capacitor reduced the phase angle between the supply voltage and source current from 25.2° to 18.2° , improving the power factor from 0.905 to 0.95. This demonstrates partial compensation of the inductive reactive power while maintaining stable operating conditions. The phasor diagram confirms this behaviour by showing the current phasor moving closer to alignment with the voltage reference.

From a power transfer perspective, power factor correction reduces the reactive component of the load impedance, allowing a greater proportion of the supply current to contribute to useful power transfer. Although the active power remains unchanged, the reduction in reactive current improves utilisation of the supply.

In terms of energy efficiency, improved power factor reduces current flow in the supply network, thereby lowering I^2R losses and thermal loading on electrical equipment. This highlights the importance of power factor correction in improving efficiency and reliability in AC power systems containing inductive loads.

7. Task 4 – Three-Phase Power Transmission

Electricity is transmitted using three-phase systems because they provide more efficient and stable power delivery compared with single-phase systems. In a balanced three-phase system, power is delivered continuously, resulting in smoother operation of motors and reduced vibration. For a given power level, three-phase transmission requires less conductor material, reducing cost and resistive losses.

Systems using more than three phases are not adopted because the additional complexity and infrastructure cost outweigh any marginal efficiency gains. Three phases represent the optimal balance between efficiency, simplicity, and reliability, which is why they are used universally in power transmission networks [5].

8. Task 5 – Practical Considerations and Limitations of Power Factor Correction

While power factor correction offers clear efficiency benefits, practical limitations must be considered [6]. Capacitors must be carefully sized to avoid over-compensation, which can result in a leading power factor and potential voltage instability [6]. In addition, power factor correction is frequency-dependent, meaning that changes in operating frequency or load conditions can affect its effectiveness.

Resonance is another important consideration in RLC systems. Although resonance produces unity power factor, it can lead to excessive circulating currents and high voltages across reactive components. For this reason, power factor correction capacitors are designed to improve power factor without tuning the circuit to resonance.

Overall, effective power factor correction requires careful design to balance efficiency improvements with system stability and component protection.

9. Discussion

This investigation examined the behaviour of a parallel RLC circuit supplied from an AC source and evaluated the effectiveness of power factor correction using a shunt capacitor. The results obtained from simulation and calculation are consistent with established AC circuit theory and demonstrate the impact of reactive components on power transfer and system efficiency.

Before power factor correction, the circuit exhibited inductive behaviour, with the source current lagging the supply voltage by approximately 25.2° . This phase displacement resulted in a lagging power factor of 0.905 and a significant reactive power component of 395.7 VAR. Although the active power delivered to the load was 840.7 W, the apparent power drawn from the supply was higher at 927.9 VA. This difference highlights the inefficiency introduced by reactive power, which increases current flow without contributing to useful energy transfer.

The presence of reactive current has important practical implications. Higher current levels increase I^2R losses in supply conductors and transformers, leading to reduced efficiency, increased heating, and unnecessary loading of electrical infrastructure. This behaviour is typical of inductive loads such as motors and transformers, reinforcing the relevance of power factor correction in real-world AC systems.

The application of a shunt capacitor provided leading reactive power that partially cancelled the lagging reactive power of the inductive load. By selecting a capacitor value of approximately $4.45\ \mu\text{F}$, the reactive power demand was reduced by 120 VAR, improving the power factor to the target value of 0.95. Importantly, the active power remained unchanged, demonstrating that power factor correction does not alter the operating characteristics of the load but instead improves the efficiency of power delivery from the supply.

The effectiveness of power factor correction is clearly illustrated by the phasor diagram. Prior to correction, the current phasor lagged significantly behind the voltage reference, indicating a large reactive component. After correction, the phase angle was reduced to 18.2° , and the current phasor moved closer to alignment with the voltage phasor. This visual representation confirms the reduction in reactive power and supports the calculated improvement in power factor.

Resonance is closely related to power factor correction in RLC circuits. At resonance, inductive and capacitive reactances are equal, causing reactive effects to cancel and the power factor to approach unity. However, operating at resonance can lead to excessive circulating currents and high voltages across reactive components, potentially damaging equipment. In this study, the capacitor was deliberately sized to improve power factor without tuning the circuit to resonance, ensuring stable operation while still achieving meaningful efficiency gains.

The frequency-based phasor analysis further reinforces this relationship. Below resonance, capacitive effects dominate and current leads voltage; above resonance, inductive effects dominate and current lags voltage. At the nominal supply frequency of 50 Hz, the circuit remained slightly inductive, but the addition of the correction capacitor reduced the phase displacement without forcing resonant conditions. This demonstrates good engineering practice in power factor correction design.

From a maximum power transfer perspective, reducing reactive power improves utilisation of the supply by allowing a greater proportion of the current to contribute to active power delivery. While the absolute active power is determined by the load, power factor correction reduces unnecessary current flow, supporting more efficient operation of the supply network.

Overall, the results confirm that power factor correction is an effective method for improving energy efficiency and system performance in AC circuits containing inductive loads. The combination of waveform analysis, power calculations, and phasor diagrams provides a clear and coherent explanation of the observed behaviour.

10. Conclusion

This report investigated the behaviour of a parallel RLC circuit supplying an inductive load and demonstrated the application of power factor correction using a shunt capacitor. A Proteus simulation was used to analyse the voltage and current waveforms, allowing the phase difference between them to be measured and the electrical power quantities to be calculated. The results confirmed that the inductive load caused the current to lag the voltage, producing a lagging power factor and a significant reactive power component.

By calculating and applying an appropriately sized capacitor, the reactive power demand of the load was reduced, and the power factor was improved to the target value of 0.95. The phasor diagram and recalculated phase angle clearly showed improved alignment between voltage and current, confirming the effectiveness of the power factor correction. Importantly, the active power remained unchanged, demonstrating that power factor correction improves efficiency by reducing unnecessary current flow rather than increasing useful power consumption.

The analysis highlights the importance of power factor correction in AC systems, particularly in industrial applications where inductive loads are common. Improving power factor reduces losses, improves utilisation of supply equipment, and supports efficient and reliable operation of electrical power systems.

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