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Impact of Inductance and Resistance on LED Performance in Series RL Circuits: A Comprehensive Study

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Abstract: This study focuses on the circuit design and operation of RL circuits with a green LED operated from an AC power source simulated using Proteus software. The source consists of a 100-ohm resistor and a 0.1 H inductor connected in parallel with the LED to regulate its operation. The circuit was simulatively examined to observe how varying resistance, inductance, and frequency affect the brightness of the LED. The high-frequency impedance of the inductor plays a critical role in channelling currents through the LED during the positive half-cycle of the AC input. For RL circuits, transient and steady-state phenomena, such as phase shifts and impedance characteristics, are studied and analysed. These circuits find applications in filtering and phase shift networks. The study highlights the importance of RL circuits in enhancing fundamental electrical engineering concepts, aiding in practical circuit design and theoretical understanding of AC circuit behaviour.

Keywords – Inductor; AC source; LED; Resistor; AC Voltmeter.

I. Introduction

In a series RL circuit, the resistor (R) and inductor (L) are connected in series, meaning that the current flowing through the circuit passes through both the resistor and the inductor equally. The inductor in the circuit generates a magnetic field as current flows through it, storing energy in the form of an electromagnetic field. It will be released back to the circuit upon decrease of the current, opposing variation of so. The resistance adds to dampening the flow of current and dissipates some energy usually by heat in accordance with what the inductor stores. In a series circuit, both the Inductance and Resistance play crucial roles in determining the behaviour of the current and voltage.

The current (I) is the same through both the resistor and the inductor as they are in series [1]. The voltage across the entire circuit is the sum of the voltage drops across the resistor and inductor shown in equation (1), denoted as;

$$V = V_R + V_L \tag{1}$$

where V_R is the voltage drop across the resistor and V_L is the voltage drop across the inductor. The voltage can be computed in the circuit across resistor and inductor by using the equation (2) and (3);

$$V = IR \tag{2}$$

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$$V = I\mathrm{L} \quad (3)$$

Since the current is the same throughout the series circuit, $I_R = I_L = I$ The voltage drop across each component depends on the reactance of the inductor and the resistance of the resistor $V_R = IR$ and $V_L = L\frac{dI}{dt}$, where $\frac{dI}{dt}$ is the rate of change of current. This circuit is commonly used in filtering, phase shift applications, and power supply designs due to its frequency-dependent characteristics.

II. Methodology

We have designed this circuit using proteus software with a focus on safety and ability of the circuit to perform its intended function. The circuit consists of a resistor R = 100 Ω, an inductor of L = 0.1H and a Green LED. The LED has electrical parameters: forward voltage of 2 V, full drive current of 10 mA and breakdown voltage of 5 V. Such parameters are necessary to make sure that the LED is kept safe even when the conditions in the circuit vary. The components of the circuit are the resistor and the inductor which are connected in a series combination forming the basic configuration of an RL (resistor-inductor) circuit, with an LED connected in parallel to the inductor. The reason for connecting the LED in parallel is to allow the current to flow through the inductor and bypass the LED when the inductor's resistance alters due to AC signal. An AC source of 5 V peak amplitude forms the whole circuit in that, it supplies an alternating current that allows the RL circuit to exhibit a time-varying response. This alternating feature is important for the LED as it allows the LED to be driven by an electrical current that results in the LED periodically turning on and off- the pattern of light behavior providing feedback on the status of the circuit. In general, this installation is perfect showing the working of an RL circuit with an LED where the direction of current flow is indicated by the LED lighting up in real time.

Circuit Diagram

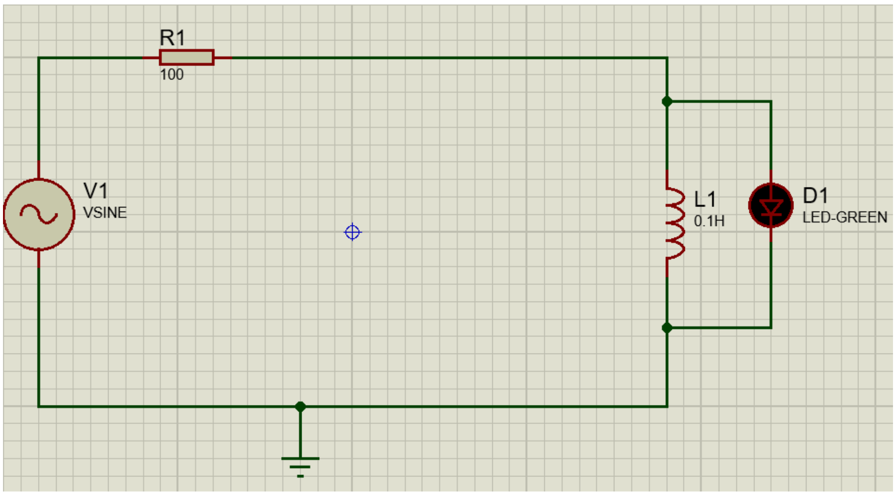

Figure 1. Schematic diagram of RL circuit.

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In order to verify that the LED would light up in the circuit which consists of an AC source with a resistance in series with an inductor, and the LED in parallel with the inductor, we will check the voltage across the inductor, and had a forward voltage across the LED and so on. The behavior of the LED in an AC circuit is shown in Figure 1.
In an AC circuit, the inductor causes a phase shift between current and voltage, and its impedance Z_L is frequency-independent given in equation (4):

$$Z_L = j\omega L = j2\pi f \tag{4}$$

Where f is the frequency of the AC source and L is the inductance.

The voltage across the inductor $V_L(t)$ in an AC circuit is calculated by the equation (5) as:

$$V_L(t) \;=\; V_{in} \cdot \frac{Z_L}{Z_R + Z_L} \tag{5}$$

LED Behaviour

When voltage across the LED gets to a point where it exceeds that threshold voltage (generally between 2 and 3 volts for most LEDs), the LED will glow. The LED is a diode that permits current to flow in only one direction i.e., when forward-biased. In an AC circuit, the LED will only conduct on half of the AC cycle (the positive forward bias). Basically, the LED will glow if the voltage across the inductor exceeds the forward voltage V_{LED} during the positive half-cycle of the waveform.

Mathematically, the equation (6) can be represented as;

$$V_L(t) > \; V_{LED} \tag{6}$$

The RMS value of the voltage across the inductor is given in the equation (7) as:

$$V_{L(rms)} \;=\; V_{in(rms)} \times \frac{\omega L}{\sqrt{R^2 + (\omega L)^2}} \tag{7}$$

From the equation (8), the condition persists for a LED to glow is given as;

$$V_{L(rms)} > V_{LED} \tag{8}$$

III. Literature Review

As per the analysis carried out by Charles. K Alexander et al., the transient behaviour of fundamental components such as resistor (R) and inductor (L) included in series RL circuit were observed with the interaction with the applied voltage [2]. They describe how the current rises exponentially over time, governed by the time constant given in equation (9);

$$\tau = L/R \tag{9}$$

The current *I(t)* is given by the equation (10) [3];

$$I(t) = \; V/R\; (1 - e\text{^}(-RLt)\;) \tag{10}$$

The discussion was made on how, after a sufficient time, the circuit reaches a steady-state where the current is constant, calculated using equation (11) [4] as;

$$I_{max} = \frac{V}{R} \quad (11)$$

In the context of AC circuits, Alexander et al. analyses the impedance of the series RL circuit, expressed by the equation (12) as:

$$Z = R + j\omega L \quad (12)$$

From equation (13), the phase angle (ϕ) between the voltage and current [5], is given as;

$$\emptyset = \left(\frac{\omega L}{R}\right) \quad (13)$$

Alexander et al. highlighted practical applications of series RL circuits, including their use in various applications such as filters, oscillators, and inductive loads, emphasizing their importance in both theoretical and practical electrical engineering [6]. Overall analysis combines theoretical foundations with practical applications, making it a valuable resource for understanding series RL circuits.

IV. Results and Discussion

Table 1. Summary of LED state.

FREQUENCY (Hz)	INDUCTOR(H)	RESISTANCE (Ω)	LED (ON/OFF)
0	0.1	100	OFF
10	0.1	100	OFF
20	0.1	100	OFF
30	0.1	100	OFF
40	0.1	100	OFF
50	0.1	100	OFF
60	0.1	100	OFF
70	0.1	100	OFF
80	0.1	100	OFF
90	0.1	100	OFF
100	0.1	100	OFF
1000	0.1	100	ON
2000	0.1	100	ON
3000	0.1	100	ON
4000	0.1	100	ON
5000	0.1	100	ON
6000	0.1	100	ON
7000	0.1	100	ON
8000	0.1	100	ON
9000	0.1	100	ON
10000	0.1	100	ON
20000	0.1	100	ON
30000	0.1	100	ON

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From Table 1, the inductor at low frequencies presents a short-circuit path for current as it shows least resistance. Because current will look for the path of least resistance, much more it passes directly through the inductor instead of going partially into another branch where is placed a LED [7]. This forces the current to flow around (outstrip) this LED again, so it will not glow. However, as the frequency will increases the inductor impedance which effectively opens it and leaves unaffected. The high impedance of this inductor makes the current unable to flow through it and force it to transit by the path where an LED is included. Therefore, the LED is powered on at more frequently rates.

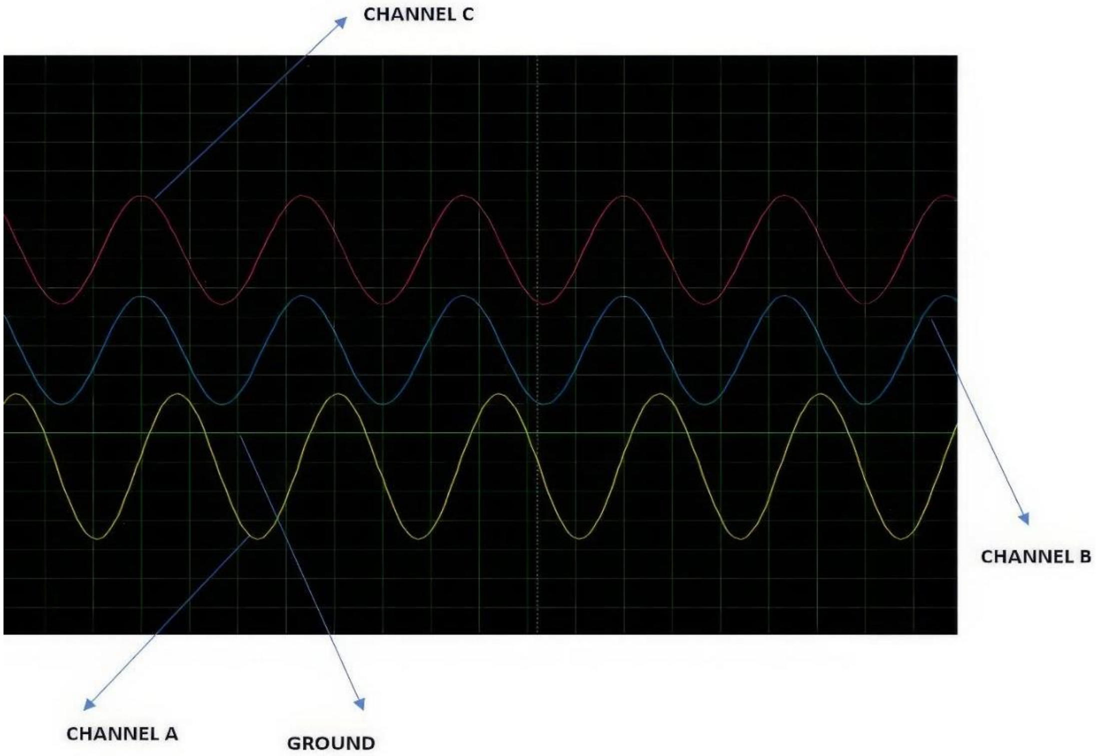

Figure 2. The Sinusoidal wave for the circuit.

Wire was connected through Channel A in the oscilloscope from the resistor to the AC source. Channel B input was obtained from the midpoint where the inductor connects to the resistor, producing a simultaneous observation of the voltage across those two components. The connection to channel C is taken from the cathode side of the LED, allowing one to view the behaviour of the LED with respect to the rest of the circuit. Finally, the ground was joined to the D terminal of the digital oscilloscope, making it possible to achieve a common reference point for readings. This setting is intended for the display of a sinusoidal waveform, in which one can find input running from the AC source. Various channels of the oscilloscope allow us to see how each individual component responds to the AC signal, the phase differences, and verification of the operation of each section in real-time concerning the LED response in the RL circuit.

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V. Conclusion

This RL circuit is an LED designed and simulated with Proteus software, demonstrating the behaviour of an AC-driven circuit effectively. The circuit comprises a 100-Ω resistor and a 0.1 H inductor connected in series, allowing the LED to operate safely under normal electrical limits. This respond directly on the time domain highlighted the RL components being connected to a 5V-Ac source, making its LED blink on and off. This blinking is the visible flow of the current, giving an intuitive insight into how RL circuits interface with an AC supply. This configuration is greatly helpful for phase relationship and energy dissipation understanding.

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