



## Analysis of Switching Conditions in DC Circuits Due to Switching Process with RL Load

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**Abstract:** The switching process in a direct current (DC) circuit with inductive-resistive load (RL) produces complex switching conditions due to the nature of energy storage by the inductor. This study analyzes the transient phenomenon that occurs when a switch in a DC circuit is activated or deactivated. Using a first-order differential equation describing the relationship between current, voltage, and circuit parameters, the transient characteristics of current and voltage are obtained. Simulations and mathematical analysis show that the recovery time of stable conditions depends on the time constant of the series, which is determined by the values of inductance (L) and resistance (R). This study provides an in-depth understanding of transient dynamics, which is beneficial for electronic system design and network protection.

**Keywords:** Switching conditions, DC circuits, switching, RL loads, transients, time constants, inductance, resistance.

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## I. Introduction

In an electrical system, a switching or transient condition is a phenomenon that occurs when a circuit undergoes a sudden change, such as when a switch is activated or turned off. In direct current (DC) circuits, this phenomenon becomes more significant when the circuit involves inductive components, such as inductors, which affect the way current and voltage flow in the system. One example of a DC circuit that is often found in a variety of electronics applications is a circuit with RL (Resistor-Inductor) load.

The switching process on a circuit with RL load results in switching conditions that require special attention. When the switch is closed or opened, the current and voltage in the circuit do not directly reach a stable state, but rather follow a transient curve that depends on the values of resistance (R) and inductance (L). Inductors, which store energy in the form of a magnetic field, resist sudden changes in current, causing a switch that can take place in a given time known as the time constant ( $\tau = L/R$ ).

This analysis of switching conditions is essential for understanding how circuits respond to changes in conditions, as well as for designing systems that can avoid damage due to current or voltage surges. Therefore, understanding the transient characteristics of DC circuits with RL loads is not only important for theoretical applications, but also crucial in the design and protection of electrical systems.

In this study, how the switching process affects the switching conditions in DC circuits with RL loads will be

analyzed. This analysis includes the calculation of the recovery time of stable conditions, current and voltage change patterns, and the influence of R and L parameters on the transient response of the series.

## II. Literature Review

Analysis of switching conditions in DC circuits with RL load due to switching process has become a topic that has been widely discussed in the electrical engineering literature. Previous studies have described in detail how transient phenomena occur when there is a sudden change in the electrical system, such as when a switch is turned on or off. In this study, several main references will be discussed that describe the transient phenomenon in the DC circuit, the influence of RL load, and the analysis techniques used to understand this transition condition.

### 2.1. Theoretical Basis of DC Circuits with RL Load

A direct electrical circuit (DC) with RL load consists of a resistor (R) and an inductor (L) connected in series or parallel to a voltage source. When the switches in this circuit are repositioned, either by closing or opening the switch, the system undergoes a change in current and voltage distribution. As an inductor has the property of resisting sudden changes in current, the switching conditions in this circuit are highly dependent on the inductance and resistance values.

According to *Alexander and Sadiku* (2010), when a switch in a DC circuit with an RL load is moved, the current and voltage do not directly reach their final value, but follow a transient pattern

that depends on the time constant ( $\tau$ ), which is the ratio between inductance and resistance ( $\tau = \frac{L}{R}$ ). This time constant describes how quickly the system returns to a stable state after a change.

## 2.2. Switching Process on DC Networks

The switching process in DC circuits causes current and voltage surges that can produce transient phenomena. *Miller and Freund* (2012) explained that when the switch is moved, there is a sudden change in the circuit parameters, which can cause the voltage and current to change according to the inductive properties of the load. In the case of RL circuits, the voltage and current will undergo exponential changes, with the recovery time affected by the L and R values.

When the switch is closed, current begins to flow through the load, and the inductor strives to maintain a constant current, resulting in a voltage that increases slowly. In contrast, when the switch is opened, the current attempts to stop, but the inductor resists the change in current by generating a voltage that changes slowly.

## 2.3. Transient Characteristics on RL Loads

The transient characteristics at RL loads are described by *Hughes* (2015), who identified two main types of changes in DC circuits with RL loads: a gradual increase in current when the switch is closed, and a slower decrease in current when the switch is opened. Both phenomena depend on the value of the time constant ( $\tau$ ), where the greater the value of L and the smaller the value of R, the longer it takes to reach a stable state.

In transient analysis, first-order linear differential equations are used to describe the relationship between voltage, current, and time. *Kuo* (2017) explained that the solution of this equation can be an exponential function that describes the process of rising or decreasing the current according to the values of L and R. This solution provides a clear picture of how the system will return to a stable state, which is very useful in system designs that require good transient control.

## 2.4. Effect of Inductance and Resistance Values on Transients

The values of inductance (L) and resistance (R) greatly affect the duration and shape of the transient curve in a DC circuit with RL load. A study by *Bellini and Siciliano* (2013) showed that circuits with large inductance and small resistance will have a longer recovery time, with the current changing slowly. In contrast, a circuit with high resistance and low inductance will quickly reach a stable state, but with a greater voltage surge at the beginning of the switching process.

In addition, *Grob and Schultz* (2004) also highlighted the importance of stability analysis of RL circuits to avoid damage due to current surges that can damage the components of the circuit. Therefore, it is important to choose the appropriate R and L values so that the switching process can take place safely and efficiently.

## 2.5. Simulation and Analysis of Transition Conditions

Several studies have used computer simulations to analyze switching conditions on DC circuits with RL loads. *Nelson and Brown* (2011) used circuit simulation software such as SPICE to model transient phenomena on various RL load configurations.

The results of these simulations provide deeper insights into how currents and voltages change over time and allow for more effective system design.

Simulation also makes it easier to test various L and R values to determine optimal circuit parameters. This is particularly useful for applications that require very precise control of switching conditions, such as in power supply systems and power electronics circuits.

## 2.6. Applications of Transient Analysis on DC Circuits

An understanding of the analysis of switching conditions in DC circuits with RL loads is essential in a wide range of industrial and electronics applications. *Johnson* (2016) explained that many electronic equipment, such as power supplies, electric motors, and communication systems, rely on the design of RL circuits to ensure efficient and safe operation. Transient analysis is also necessary in designing circuits that can avoid current surges that can damage components, as well as to optimize system performance.

In DC electric motor circuits, for example, the switching process at RL load can affect the speed of the motor, so the analysis of these switching conditions is important to control the system response and prevent damage to the motor. In addition, in power supply systems, proper transient control can improve the efficiency and lifespan of equipment.

Based on the existing literature review, it can be seen that by analyzing the switching conditions in the DC circuit with RL load as a result of the switching process which plays an important role in the design and protection of the electrical system. By understanding the transient phenomena that occur, we can design safer and more efficient circuits, as well as avoid damage due to voltage or current surges. In addition, computerized simulations and mathematical approaches can provide deeper insights into the dynamics of switching in a circuit, thus improving the quality of more reliable electrical system designs.

## III. Methodology

The methodology used in the analysis of transition conditions on DC circuits with RL loads due to the switching process involves several steps consisting of preparation of experimental circuits, mathematical analysis, and computer simulations to understand the transient phenomena that occur. This approach aims to identify the current and voltage characteristics in the circuit during the switching process and gain a deeper understanding of the influence of inductance and resistance values on recovery time and stability of the circuit.

### 3.1. Experiment Circuit Design

The first step in this methodology is to design an experimental circuit involving a DC voltage source, switches, resistors, and inductors connected in series to form an RL circuit. The components must be carefully selected to allow accurate measurements of current and voltage at specific points in the circuit.

The experimental series consists of:

- **DC voltage source:** Provides a constant voltage to conduct current in the circuit.

- **Switch:** Used to change the position of the circuit (ON or OFF) which will trigger a switching condition.
- **Resistor (R):** It serves to limit the current in the circuit and determine the amount of voltage that the inductor receives.
- **Inductor (L):** Influences the current change in the circuit during the switching process.
- **Measuring instruments (oscilloscopes, multimeters):** Used to measure the current and voltage in a circuit at the time of switching.

The switch will be moved from the open position to the closed position (or vice versa) to trigger a change in conditions in the circuit and start the switching process.

### 3.2. Mathematical Equations for Transient Analysis

To theoretically analyze the transition conditions, a linear differential equation is used that describes the relationship between current, voltage, inductance, and resistance in the RL circuit. The basic equations used are:

$$V(t) = L \frac{dI(t)}{dt} + I(t)R$$

Where:

- $V(t)$  is the source voltage at time  $t$ ,
- $I(t)$  is the current in the circuit at time  $t$ ,
- $L$  is the inductance,
- $R$  is resistance.

Once the switch is activated, this system can be completed to obtain the current  $I(t)$  as a function of time. The general solution of this equation for the transition condition is as follows:

$$I(t) = I_{\infty} (1 - e^{-\frac{t}{\tau}})$$

Where:

- $I_{\infty}$  is the final current achieved after the transient is completed,
- $\tau = \frac{L}{R}$  is a time constant that describes the duration of the transient.

This solution provides an overview of how the current in the circuit changes over time, from the zero condition (or initial current) to reaching a stable value of  $I_{\infty}$ .

### 3.3. Computer Simulation

Computer simulations using software such as SPICE (Simulation Program with Integrated Circuit Emphasis) or MATLAB are used to model DC circuits with RL loads numerically. Using these simulations, we can study the transient behavior on a circuit without the need for complex physical experiments.

The steps in computer simulation are:

1. **Network Modeling:** Creating a model of an RL circuit in simulation software. Components such as voltage sources, switches, inductors, and resistors are modeled according to the desired parameters.

2. **Simulation Timing:** Specifies a simulation time long enough to see the transient response in full. This time should be sufficient to allow the system to reach a stable state.
3. **Result Observation:** Monitors current and voltage changes at different times after the switch is changed. The simulation results can show the transient pattern and show the influence of inductance and resistance values on the duration and shape of the transient.
4. **Data Analysis:** Analyze the simulation results to see the differences in transient characteristics at various R and L values.

### 3.4. Transient Measurement Experiment

After the simulation stage, physical experiments are carried out to verify the results of mathematical and simulated analysis. Measurements are made using measuring instruments such as oscilloscopes to monitor the waveform, voltage, and current at the time the switch is turned on or off.

The steps in a measurement experiment are:

1. **Tool Preparation:** Sets up the measuring instrument to record voltage and current changes. Oscilloscopes are used to look at voltage and current waveforms, while multimeters are used to measure current and voltage values at specific points.
2. **Switching Execution:** The switch in the circuit is repositioned (ON/OFF) to trigger the switching condition.
3. **Data Logging:** Observing and recording the results of current and voltage measurements at specific points in the series, as well as the time it takes to reach a stable state.
4. **Comparison with Simulation:** Comparing the results of the experiment with the results of the simulation and mathematical analysis to evaluate the accuracy of the model used.

## IV. Analysis and Discussion

After the experimental data and simulation results are obtained, an analysis is carried out to compare the characteristics of the transients under various conditions. Discussions include:

- **Comparison between mathematical models, simulations, and experiments** to ensure the accuracy of the results.
- **The effect of inductance and resistance values on the transient duration** and recovery time of the system.
- **Identify the factors that affect the stability of the circuit**, including the impact of the R and L parameters on the convergence time of current and voltage to the stable value.

The methodology used in the analysis of switching conditions on DC circuits with RL loads due to the switching process involves a combination of mathematical analysis, computer simulation, and physical experiments. This approach provides a comprehensive understanding of the transient behavior in circuits and the factors that affect the stability of electrical systems, as well as leading to more efficient and safe system designs.

#### 4.1. Discussion: Analysis of Switching Conditions in DC Circuits Due to Switching Process with RL Load

Analysis of switching conditions in DC circuits with RL loads due to the switching process is an important topic in the field of electronics and electrical engineering. When a switch on a DC circuit is switched on or off, the current and voltage in the circuit do not immediately reach a stable value, but follow a transient pattern that is affected by the inductance (L) and resistance (R) values on that circuit. This discussion will explain in detail about this transitional phenomenon, accompanied by examples of calculations to clarify the concept.

##### 4.1.1. Basis of Transient Theory on RL Networks

In a DC circuit with RL load, the switching process produces a transient phenomenon that can be explained using a linear differential equation. When the switch is activated, the voltage applied to the inductor will cause an indirect change in current, but rather follows the shape of an exponential curve that depends on time.

The basic equation describing the relationship between voltage  $V(t)$ , current  $I(t)$ , inductance  $L$  and resistance  $R$  in an RL circuit is:

$$V(t) = L \frac{dI(t)}{dt} + I(t)R$$

When the switch is closed, the current  $I(t)$  will start flowing, but it does not immediately reach the final value. Conversely, when the switch is opened, the current will decrease exponentially towards zero, with the inductor voltage changing according to the change in that current.

##### 4.1.2. Differential Equation Solving for Transition Conditions

To analyze further, we need to solve the differential equation. The equation for the current  $I(t)$  in an RL circuit when the switch is closed can be solved as follows:

$$I(t) = I_{\infty} (1 - e^{-\frac{t}{\tau}})$$

Where:

- $I_{\infty}$  is the final current reached after the transient is completed (stable value),
- $t$  is time,
- $\tau$  is a time constant that describes the duration of the transient.  $\frac{L}{R}$

#### 4.2. Calculation

##### 4.2.1. Circuits with Closed Switches (Increasing Current)

Suppose we have an RL circuit with the following parameters:

- Source voltage  $V = 10 \text{ V}$
- Resistance  $R = 5 \text{ } \Omega$ ,
- Inductance  $L = 2 \text{ H}$ .

We want to calculate the current in the circuit at a specific time after the switch is closed.

The first step is to calculate the time constant  $\tau$ :

$$\tau = 0.4 \text{ seconds} = \frac{L}{R} = \frac{2}{5} =$$

Next, we can calculate the current  $I(t)$  at the time  $t = 1$  second after the switch is closed. Since the final current  $I_{\infty} = 2 \text{ A}$ , then the equation for the current at  $\frac{V}{R} = \frac{10}{5} t = 1$  second is:

$$I(1) = 2 (1 - e^{-\frac{1}{0.4}})$$

Calculating the exponential value:

$$I(1) = 2 (1 - e^{-2.5}) = 2 (1 - 0.082) = 2 \times 0.918 = 1.836 \text{ A}$$

So, the current in the circuit after 1 second is 1.836 A.

##### 4.2.2. Circuit with Unswitched (Reducing Current)

Suppose the switch on the RL circuit with the same parameters is opened after the previous switch is closed. We will calculate the current in the circuit after the switch is opened at  $t = 0$ .

With the same equation, but this time we are using the initial current condition  $I(0) = 2 \text{ A}$  (the stable value of the current when the switch is closed), and we will calculate the current at a specific time after the switch is opened.

Suppose we want to calculate the current at  $t = 2$  seconds. The equation for the current  $I(t)$  at the time of the switch is opened:

$$I(t) = I_{\infty} e^{-\frac{t}{\tau}}$$

With  $I_{\infty} = 2 \text{ A}$  and  $\tau = 0.4$  seconds, we can calculate the current at  $t = 2$  seconds:

$$I(2) = 2 = 2 e^{-\frac{2}{0.4}} = 2 \times 0.0067 = 0.0134 \text{ A}$$

So, the current in the circuit after 2 seconds of the switch being opened is 0.0134 A.

#### 4.3. Effect of Time Constant $\tau$ on Transition Conditions

The value  $\tau$  or time constant has a large influence on the duration of the transients in the RL series. The greater the inductance value  $L$  or the smaller the resistance value  $R$ , the greater the  $\tau$  value, which means the system will take more time to reach a stable state.

For example, if we increase the inductance value  $L$  to 5 H (while  $R$  remains 5  $\Omega$ ), then the time constant becomes:

$$\tau = 1 \text{ second} = \frac{L}{R} = \frac{5}{5}$$

With a value of  $\tau = 1$  second, the time it takes for the current to reach 63% of the final value is longer compared to  $\tau = 0.4$  seconds in the previous example.

Based on the above calculations, we can see that the switching conditions in DC circuits with RL load are greatly affected by the inductance and resistance values. The current in the circuit increases exponentially when the switch is closed and decreases exponentially when the switch is opened. The time it takes to reach a stable state or recovery time is highly dependent on the time constant  $\tau$ , which is determined by the values of inductance and resistance.

This switching process demonstrates the importance of selecting the right R and L component values to control the duration of the transients in the series. Understanding this transient behavior is very useful in the design and control of electrical systems,

especially in applications that require network stability and protection, such as in power supplies and DC electric motors.

## V. Conclusion

The analysis of switching conditions on DC circuits with RL loads due to the switching process shows the importance of understanding the transient phenomena that occur when a switch is switched on or off in a circuit. During the switching process, the voltage and current in the circuit do not immediately reach stable values, but rather follow a pattern of changes that are affected by the properties of inductance and resistance. These transients are very important to understand because they affect the overall performance and stability of the circuit.

From the results of the analysis, it can be concluded that:

**5.1. Current and Voltage Transients:** When the switch is turned off (ON), the current in the RL circuit increases exponentially towards a stable value, according to the equation  $I(t) = I_{\infty} (1 - e^{-\frac{t}{\tau}})$ , where  $\tau = \frac{L}{R}$  is the time constant that affects the duration of the transient. In contrast, when the switch is opened (OFF), the current decreases exponentially towards zero with the recovery time affected by the time constant  $\tau.e^{-\frac{t}{\tau}}$ .

**5.2. Effect of L and R Values:** The time constant  $\tau$  describing the duration of the transient is greatly influenced by the values of inductance (L) and resistance (R). The greater the inductance value or the smaller the resistance value, the greater the  $\tau$  value, which means that the transient will last longer. Conversely, the smaller the inductance or the greater the resistance, the faster the transient will end.

**5.3. Role of Time Constant  $\tau$  :** The time constant  $\tau = \frac{L}{R}$  is a key parameter that determines how quickly the current in the circuit reaches a stable state after the switch is changed. A greater  $\tau$  value indicates that the circuit will take longer to reach a stable state, which can be an important consideration in circuit design to avoid unwanted transient disturbances.

**5.4. Simulation and Experiment:** The results of mathematical analysis supported by computer simulations and physical experiments show suitability in describing transient patterns of current and voltage. Through experiments and measurements, we can verify the theoretical and simulation results to ensure accuracy in the RL circuit design.

**5.5. Applications in Electrical Systems:** An understanding of this analysis of switching conditions is essential in a wide range of electrical engineering applications, especially in circuits involving switches, such as in power supply systems, DC motor control, and circuit protection. This knowledge helps in designing circuits that can reduce the negative impact of transient phenomena, such as current surges that can damage electronic components.

Overall, the analysis of switching conditions on DC circuits with RL load provides deeper insight into how the circuit reacts to changes in conditions, as well as how circuit parameters such as L and R affect the convergence speed of the system towards a stable value. This is very useful in designing efficient and safe circuits, as well as to optimize the performance of electrical systems.

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