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Effect of Slew-Rate Limiting On Output Sinusoidal Waveforms Analysis Methods

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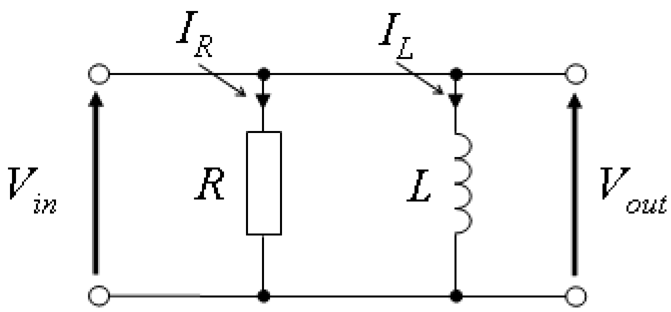
Abstract - First order circuits are circuits that contain only one energy storage element (capacitor or inductor), and that can therefore be described using only a first order differential equation. The two possible types of first-order circuits are:

1. ***RC (resistor and capacitor)***
2. ***RL (resistor and inductor)***

RL and RC circuits is a term we will be using to describe a circuit that has either a) resistors and inductors (RL), or b) resistors and capacitors (RC).

RL Circuits



An RL parallel circuit

An RL Circuit has at least one resistor (R) and one inductor (L). These can be arranged in parallel, or in series. Inductors are best solved by considering the current flowing through the inductor. Therefore, we will combine the resistive element and the source into a Norton Source Circuit. The Inductor then, will be the external load to the circuit. We remember the equation for the inductor:

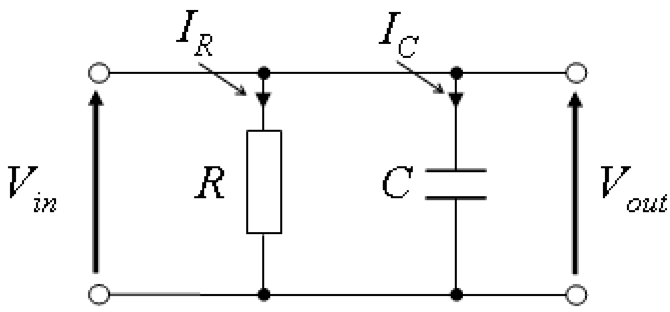
$$v(t) = L\frac{di}{dt}$$

If we apply KCL on the node that forms the positive terminal of the voltage source, we can solve to get the following differential equation:

$$i_{source}(t) = \frac{L}{R_n}\frac{di_{inductor}(t)}{dt} + i_{inductor}(t)$$

We will show how to solve differential equations in a later chapter.

RC Circuits



A parallel RC Circuit

An RC circuit is a circuit that has both a resistor (R) and a capacitor (C). Like the RL Circuit, we will combine the resistor and the source on one side of the circuit, and combine them into a thevenin source. Then if we apply KVL around the resulting loop, we get the following equation:

$$v_{source} = RC\frac{dv_{capacitor}(t)}{dt} + v_{capacitor}(t)$$

In general, from an engineering standpoint, we say that the system is at steady state (Voltage or Current is almost at Ground Level) after a time period of five Time Constants.

Key words: circuits, resistor and capacitor, resistor and inductor, inductors.

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INTRODUCTION

When circuits get large and complicated, it is useful to have various methods for simplifying and analyzing the circuit. There is no perfect formula for solving a circuit. Depending on the type of circuit, there are different methods that can be employed to solve the circuit. Some methods might not work, and some methods may be very difficult in terms of long math problems. Two of the most important methods for solving circuits are **Nodal Analysis**, and **Mesh Current Analysis**. These will be explained below.

Superposition

One of the most important principals in the field of circuit analysis is the principal of **superposition**. It is valid only in linear circuits.

The **superposition principle** states that the total effect of multiple contributing sources on a linear circuit is equal to the sum of the individual effects of the sources, taken one at a time.

What does this mean? In plain English, it means that if we have a circuit with multiple sources, we can "turn off" all but one source at a time, and then investigate the circuit with only one source active at a time. We do this with every source, in turn, and then add together the effects of each source to get the total effect. Before we put this principle to use, we must be aware of the underlying mathematics.

REVIEW OF LITERATURE

Superposition can only be applied to **linear** circuits; that is, all of a circuit's sources hold a linear relationship with the circuit's responses. Using only a few algebraic rules, we can build a mathematical understanding of superposition. If *f* is taken to be the response, and *a* and *b* are constant, then:

$$f(ax_1 + bx_2) = f(ax_1) + f(bx_2)$$

In terms of a circuit, it clearly explains the concept of superposition; each input can be considered individually and then summed to obtain the output. With just a few more algebraic properties, we can see that superposition cannot be applied to non-linear circuits. In this example, the response *y* is equal to the square of the input x, i.e. $y=x^2$. If *a* and *b* are constant, then:

$$y = (ax_1 + bx_2)^2 \neq (ax_1)^2 + (bx_2)^2 = y_1 + y_2$$

Note that this is only one of an infinite number of counter-examples...

Step by Step

Using superposition to find a given output can be broken down into four steps:

1. Isolate a source - Select a source, and set all of the remaining sources to zero. The consequences of "turning off" these sources are explained in [Open and Closed Circuits](). In summary, turning off a voltage source results in a short circuit, and turning off a current source results in an open circuit. (Reasoning -

no current can flow through a open circuit and there can be no voltage drop across a short circuit.)

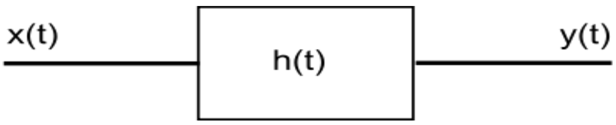
2. Find the output from the isolated source - Once a source has been isolated, the response from the source in question can be found using any of the techniques we've learned thus far.

3. Repeat steps 1 and 2 for each source - Continue to choose a source, set the remaining sources to zero, and find the response. Repeat this procedure until every source has been accounted for.

4. Sum the Outputs - Once the output due to each source has been found, add them together to find the total response.

Impulse Response

An **impulse response** of a circuit can be used to determine the output of the circuit:



The output y is the **convolution** h * x of the input x and the impulse response:

[Convolution]

$$y(t) = (h * x)(t) = \int_{-\infty}^{+\infty} h(t-s)x(s)ds$$

If the input, x(t), was an **impulse** ($\delta(t)$), the output y(t) would be equal to h(t).

By knowing the impulse response of a circuit, any source can be plugged-in to the circuit, and the output can be calculated by convolution.

The **convolution operation** is a very difficult, involved operation that combines two equations into a single resulting equation. Convolution is defined in terms of a definite integral, and as such, solving convolution equations will require knowledge of integral calculus. This wikiresearch work will not require a prior knowledge of integral calculus, and therefore will not go into more depth on this subject then a simple definition, and some light explanation.

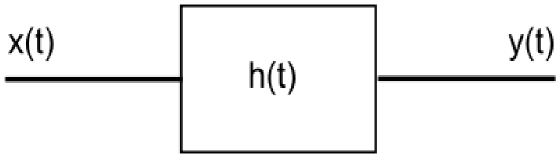
The asterisk operator is used to denote convolution. Many computer systems, and people who frequently write mathematics on a computer will often use an asterisk to denote simple multiplication (the asterisk is the multiplication operator in many programming languages), however an important distinction must be made here: **The asterisk operator means convolution**

PROPERTIES

Convolution is commutative, in the sense that $a*b = b*a$. Convolution is also *distributive* over addition, i.e. $a*(b+c) = a*b + a*c$, and *associative*, i.e. $a*(b*c) = (a*b)*c$.

Systems, and convolution

Let us say that we have the following block-diagram system:



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Properties

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Systems, and convolution

Let us say that we have the following block-diagram system:

- x(t) = system input
- h(t) = impulse response
- y(t) = system output

Where x(t) is the input to the circuit, h(t) is the circuit's impulse response, and y(t) is the output. Here, we can find the output by convoluting the impulse response with the input to the circuit. Hence we see that the impulse response of a circuit is not just the ratio of the output over the input. In the frequency domain however, component in the output with frequency ω is the product of the input component with the same frequency and the transition function at that frequency. The moral of the story is this: *the output to a circuit is the input convolved with the impulse response.*

Resistors, wires, and sources are not the only passive circuit elements. Capacitors and Inductors are also common, passive elements that can be used to store and release electrical energy in a circuit. We will use the analysis methods that we learned previously to make sense of these complicated circuit elements.

FIRST ORDER CIRCUITS

First order circuits are circuits that contain only one energy storage element (capacitor or inductor), and that can therefore be described using only a first order differential equation. The two possible types of first-order circuits are:

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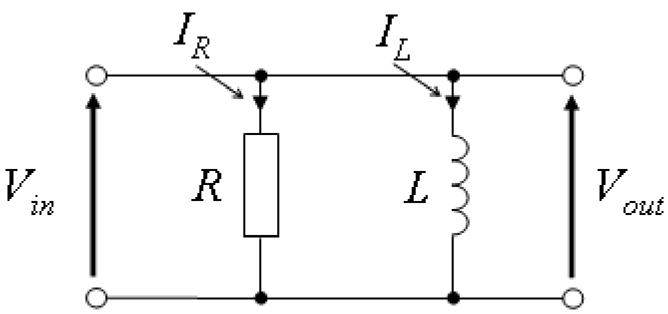

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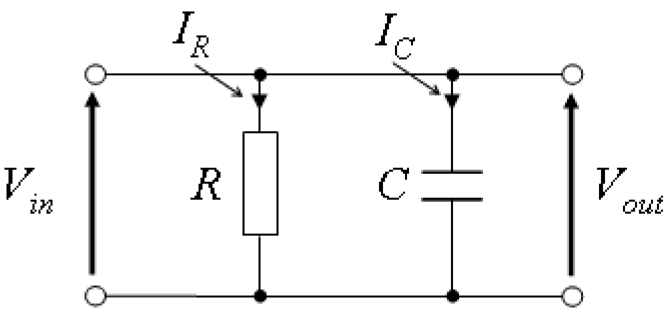

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MATERIAL AND METHOD

Series RL

The differential equation of the series RL circuit

$$L\frac{dI}{dt} + IR = 0$$

$$\frac{dI}{dt} = -I\frac{R}{L}$$

$$\frac{1}{I}dI = -\frac{R}{L}dt$$

$$\int \frac{1}{I}dI = -\frac{R}{L}\int dt$$

$$lnI = -\frac{R}{L}t + C$$

$$I = e^{(} - \frac{R}{L}t + C)$$

$$I = Ae^{(} - \frac{R}{L}t)$$. A = e^C

t	I(t)
0	A
1 $\frac{R}{L}$	36% A
2 $\frac{R}{L}$	A
3 $\frac{R}{L}$	A
4 $\frac{R}{L}$	A
5 $\frac{R}{L}$	1% A

Series RC

The differential equation of the series RC circuit

$$C\frac{dV}{dt} + \frac{V}{R} = 0$$

$$\frac{dV}{dt} = -V\frac{1}{RC}$$

$$\frac{1}{V}dV = -\frac{1}{RC}dt$$

$$\int \frac{1}{V}dV = -\frac{1}{RC}\int dt$$

$$lnV = -\frac{1}{RC}t + C$$

$$V = e^{(} - \frac{1}{RC}t + C)$$

$$V = Ae^{(} - \frac{1}{RC}t)$$. A = e^C

t	V(t)
0	A
1 $\frac{1}{RC}$	36% A
2 $\frac{1}{RC}$	A
3 $\frac{1}{RC}$	A
4 $\frac{1}{RC}$	A
5 $\frac{1}{RC}$	1% A

Time Constant

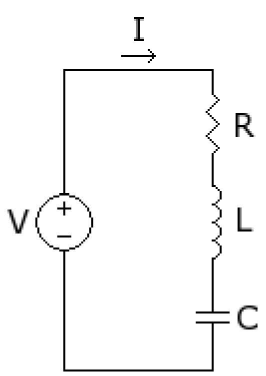
The series RL and RC has a Time Constant

$$T = \frac{L}{R}$$

$$T = \frac{RC}{1}$$

In general, from an engineering standpoint, we say that the system is at steady state (Voltage or Current is almost at Ground Level) after a time period of five Time Constants.

Series RLC Circuit



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SECOND ORDER DIFFERENTIAL EQUATION

$$L\frac{dI}{dt} + IR + \frac{1}{C}\int Idt = V$$

$$\frac{d^2I}{dt^2} + \frac{R}{L}\frac{dI}{dt} + \frac{I}{LC} = 0$$

The characteristic equation is

$$s^2 + \frac{R}{L}s + \frac{1}{LC} = 0$$

$$s = -\alpha \pm \sqrt{\alpha^2 - \beta^2}$$

Where

$$\alpha = \frac{R}{2L}$$

$$\beta = \frac{1}{\sqrt{LC}}$$

When $\sqrt{\alpha^2 - \beta^2} = 0$

$$\alpha^2 = \beta^2; R = 2\sqrt{\frac{L}{C}}$$

The equation only has one real root . $s = -\alpha = -\dfrac{R}{2L}$

The solution for $I(t) = Ae^{(}-\dfrac{R}{2L}t)$

The I - t curve would look like

When $\sqrt{\alpha^2 - \beta^2} > 0$

$\alpha^2 > \beta^2$. R > $\dfrac{L}{C}$

The equation only has two real root . $s = -\alpha \pm \sqrt{\alpha^2 - \beta^2}$

The solution for $I(t) = e^{-\alpha+\sqrt{\alpha^2-\beta^2}t} + e^{-\alpha-\sqrt{\alpha^2-\beta^2}t} = e^{-\alpha}e^{j(}$

The I - t curve would look like

When $\sqrt{\alpha^2 - \beta^2} < 0$

$\alpha^2 < \beta^2$. R < $\dfrac{L}{C}$

The equation has two complex root . $s = -\alpha \pm j\sqrt{\beta^2 - \alpha^2}$

The solution for $I(t) = e^{(-\alpha+\sqrt{\beta^2-\alpha^2}t)} + e^{(-\alpha-\sqrt{\beta^2-\alpha^2}t)} = e^{-\alpha}$

The I - t curve would look like

DAMPING FACTOR

The damping factor is the amount by which the oscillations of a circuit gradually decrease over time. We define the damping ratio to be:

Circuit Type	Series RLC	Parallel RLC
Damping Factor	$\zeta = \dfrac{R}{2L}$	$\zeta = \dfrac{1}{2RC}$
Resonance Frequency	$\omega_o = \dfrac{1}{\sqrt{LC}}$	$\omega_o = \dfrac{1}{\sqrt{LC}}$

Compare The Damping factor with The Resonance Frequency give rise to different types of circuits: **Overdamped**, **Underdamped**, and **Critically Damped**.

Bandwidth

Bandwidth

$$\Delta\omega = 2\zeta$$

For series RLC circuit:

$$\Delta\omega = 2\zeta = \frac{R}{L}$$

For Parallel RLC circuit:

$$\Delta\omega = 2\zeta = \frac{1}{RC}$$

Quality Factor

Quality Factor

$$Q = \frac{\omega_o}{\Delta\omega} = \frac{\omega_o}{2\zeta}$$

For Series RLC circuit:

$$Q = \frac{\omega_o}{\Delta\omega} = \frac{\omega_o}{2\zeta} = \frac{L}{R\sqrt{LC}} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

For Parallel RLC circuit:

$$Q = \frac{\omega_o}{\Delta\omega} = \frac{\omega_o}{2\zeta} = \frac{RC}{\sqrt{LC}} = R\sqrt{\frac{C}{L}}$$

CONCLUSION

Because inductors and capacitors act differently to different inputs, there is some potential for the circuit response to approach infinity when subjected to certain types and amplitudes of inputs. When the output of a circuit approaches infinity, the circuit is said to be **unstable**. Unstable circuits can actually be dangerous, as unstable elements overheat, and potentially rupture.

A circuit is considered to be stable when a "well-behaved" input produces a "well-behaved" output response. We use the term "Well-Behaved" differently for each application, but generally, we mean "Well-Behaved" to mean a finite and controllable quantity.

In general, from an engineering standpoint, we say that the system is at steady state (Voltage or Current is almost at Ground Level) after a time period of five Time Constants.

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