VENABLE TECHNICAL PAPER # 19

Distributed Power
What Causes These Systems to Oscillate?

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Distributed power systems can oscillate, especially when driving one power supply with another power supply. The input and output impedances of a power supply can predict this oscillation. Before looking at the specific details of the oscillation criteria we will review the basics of impedance.

Most engineers understand impedance from a dc standpoint. The assumptions for the dc impedance model (resistance) are that voltage and current never change. Impedance, by contrast, can vary with frequency. It only assumes that the circuit is linear; that is, if you apply a voltage, see the current respond, and then apply a voltage waveform twice as big, the current waveform will be the same shape and twice as big. This is often a good assumption.

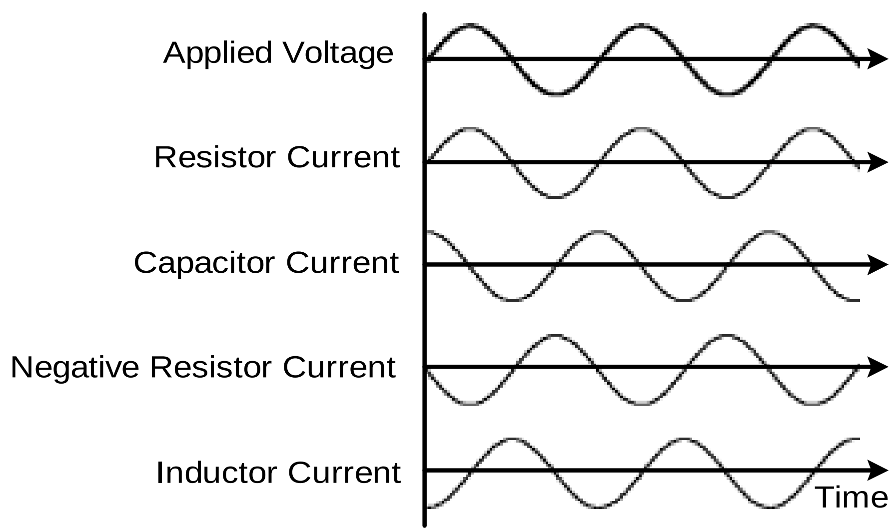


Figure 1. Voltage and current waveforms

Figure 1 shows a time graph of a sinusoidal voltage at a single frequency and the resulting current waveform for a resistor at that frequency that displays its phase characteristics: the voltage and current are in phase. It could look completely different at a different frequency. *Figure 1* also shows the resulting current waveform for a capacitor at that frequency. An ideal capacitor will have this phase relationship for all frequencies. It will also have low current at low frequency and high current at high frequency; that is, the impedance will be large at low frequency and small at high frequency. For completeness, *Figure 1* shows the current for an ideal inductor and negative resistor.

As the phase travels from 0° past 90°, past 180° and around to 360°, we have a signal that is identical. We can graph impedance at a specific frequency on a polar impedance graph, as shown in *Figure 2* on the following page. The magnitude of the impedance is the length of the line and the phase of the impedance is the phase angle from 0° or the positive x-axis. *Figure 2* also shows an ideal R, L, –R, and C on the polar impedance graph.

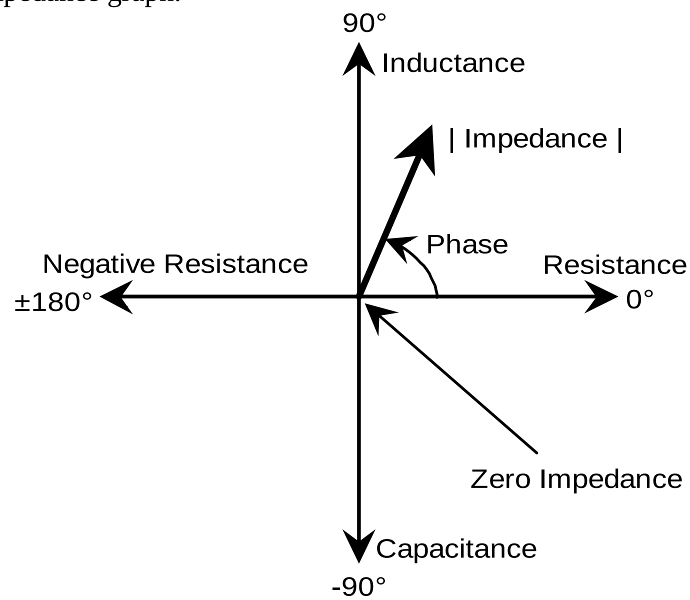
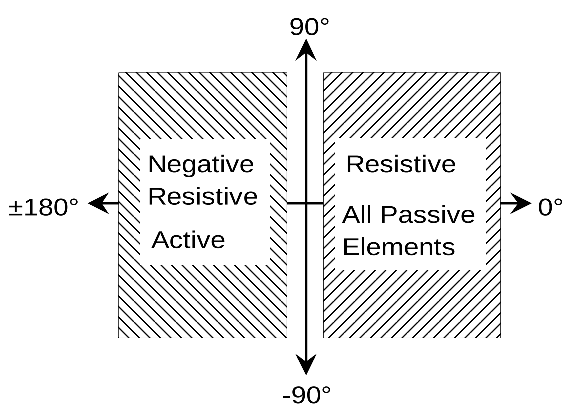


Figure 2. Polar impedance at a specific frequency

The polar impedance graph can be divided into halves. *Figure 3* shows the phase regions for impedance. An impedance called "capacitive and resistive" at a specific frequency, for instance, is equivalent to saying "the phase is between –90° and 0°."



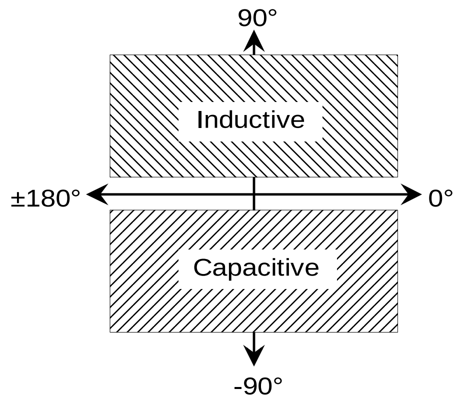


Figure 3. Half planes of polar impedance

If you are interested in creating a circuit model whose impedance has a particular phase angle at a specific frequency, choose the ideal components closest to the phase (see *Figure 4* next page). For instance, if you wanted a circuit that had an impedance with 130° of phase, combine a negative resistor with an inductor.

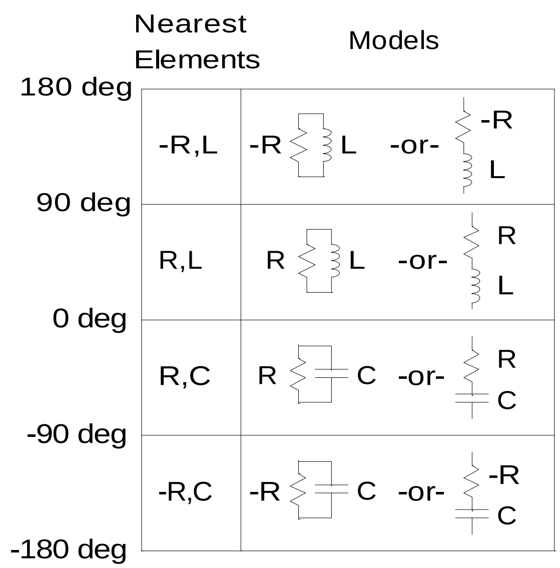


Figure 4. Impedance modeling at a specific frequency

Negative Inductance

"Negative" here means the magnitude is the same and the phase is 180° different. A negative inductor, therefore, has the magnitude graph of an inductor and a phase graph 180° from an inductor, which is the same phase as an ideal capacitor. If you only look at a single frequency, a negative inductor is indistinguishable from a capacitor. A negative inductor is a capacitor whose impedance increases with increasing frequency. This is potentially a useful element for modeling bizarre impedances.

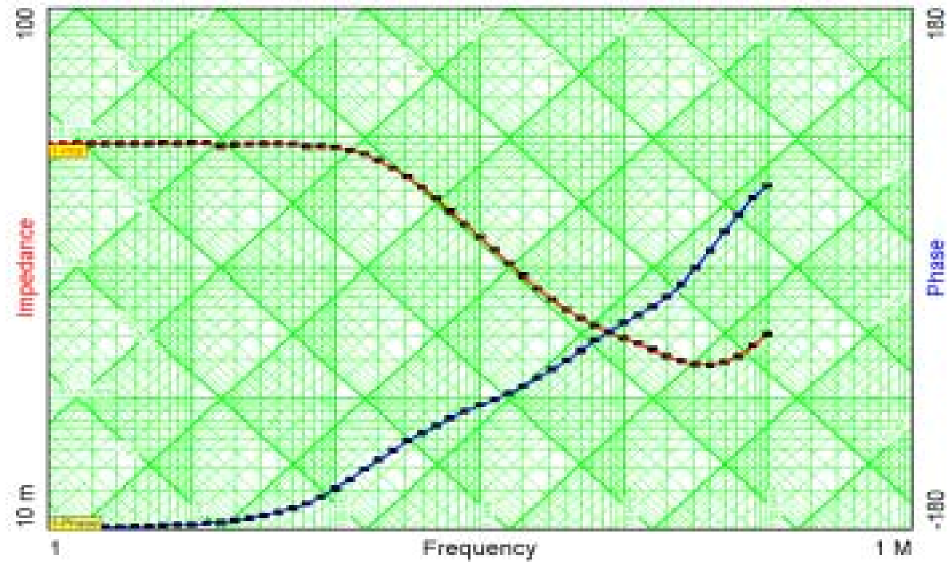


Figure 5. Power supply input impedance

We can take many polar impedance graphs, stack them together, and we will have the familiar impedance versus frequency and phase versus frequency graphs. *Figure 5* shows these graphs for a power supply input impedance. Normally we overlap them, partly to save paper and partly to correlate between the two graphs. Now we are seeing not just one frequency graph but also a whole range. Notice that the phase is shown linearly, but it is actually cyclic, i.e. –180°, +180° and 540° are indistinguishable.

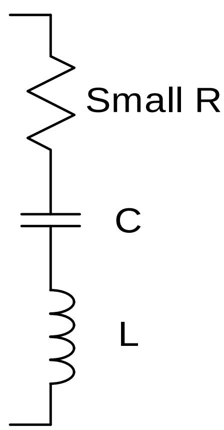


Figure 6. Series RLC circuit

We can clarify our discussion with a simple example that is familiar, the series RLC circuit. *Figure 6* shows the schematic and *Figure 7* shows the impedance using ideal parts.

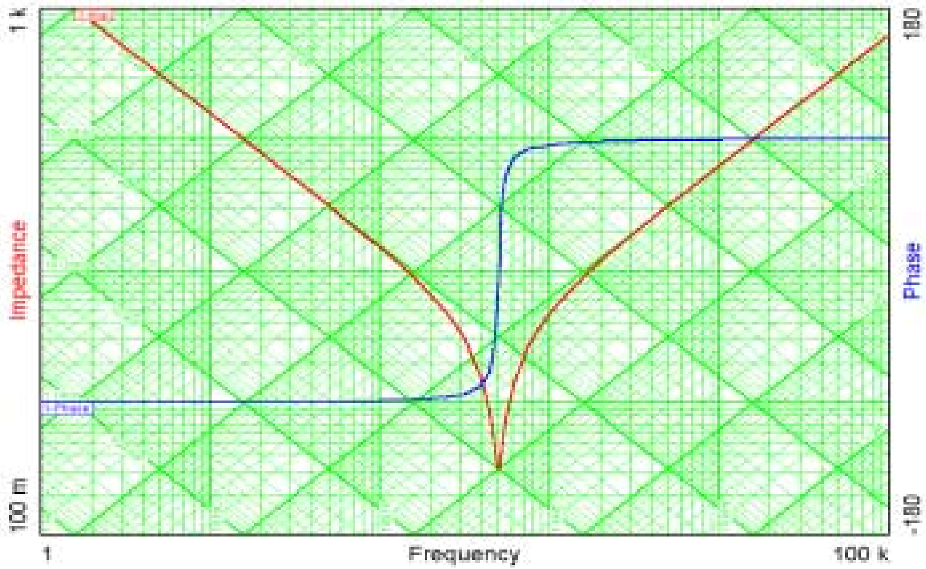


Figure 7. Impedance of series RLC circuit

At low frequency, the circuit looks and behaves like the capacitor. At high frequency the circuit behaves like the inductor. When the phase for the circuit swings through zero degrees it displays the characteristics of the resistor. If the resistor is very small the impedance of the circuit will be very small at this frequency. This frequency is where the magnitude of the impedance of the inductor matches the magnitude of the impedance of the capacitor. If there were no resistor, the impedance would go to zero, and there would be a large current with very little or no voltage. Noise would cause this ideal circuit to sustain very large currents at that specific frequency, a condition known as oscillation.

This doesn't happen in the real world because all capacitors and inductors have some inherent resistance. However, if you take a low resistance inductor and capacitor and hit them with a pulse, they will ring for a long time – until the resistance uses up the pulse energy.

Impedance Matching

Figure 8 shows a simple view of one power supply driving another. At dc, the source supplies power. The load uses power and the source impedance heats up the source.

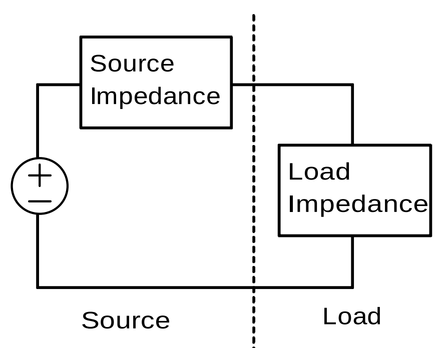


Figure 8. Simplified view of source and load

At all frequencies, the source drives the source impedance and load impedance. The source voltage is close to zero for all frequencies except dc. It is not perfectly zero volts because the system has noise in it. If the combined impedance of the load and the source equal zero ohms at any frequency, there will be a large current at that frequency for very little source voltage applied at that frequency. In other words, the system will oscillate for any frequency where:

- Source Z + Load Z = Zero

This is equivalent to the following criteria:

- Magnitude of source impedance = Magnitude of load impedance
- Phase of source impedance = Phase of load impedance +180°

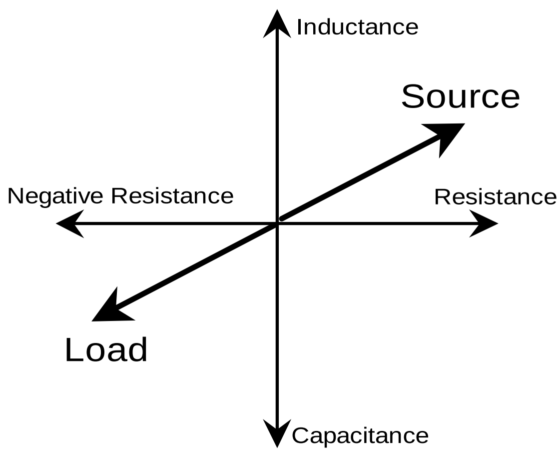


Figure 9. Polar plot of oscillation criteria

So, at any frequency where the impedances are equal in magnitude and opposite in phase, they will sum to zero impedance at that frequency and the system will oscillate. *Figure 9* illustrates this criterion in a polar graph.

All sources tend to have resistive source impedances; that is, the phase is between –90° and +90°. If the load is made of passive elements it will be a combination of capacitors, inductors and resistor. This load will always have some positive resistance; that is, the phase will be between –90° and +90°. Therefore, the phases of the source and load will never be 180° different and there cannot be oscillations when the load is made of passive elements.

The problem of oscillation seems to occur when one power supply drives another power supply – especially very efficient power supplies with input filters. Power supplies look like negative resistors at dc. Their job is to keep a constant power output over a range of input voltages. Therefore, as you increase the input voltage the input current decreases. Their phase tends toward –180° at low frequencies. If the source impedance is resistive, the phases could be 180° different, and oscillation is possible.

Figures 10 and *11* show real power supplies on the verge of oscillation. In *Figure 10*, the source and load have impedances with the same magnitude of 13mΩ and the phases are opposite around 250Hz. In *Figure 11*, the impedance magnitudes are 5.7Ω when the phases are almost opposite. Both of these systems will oscillate with just a slight change in dc voltage.

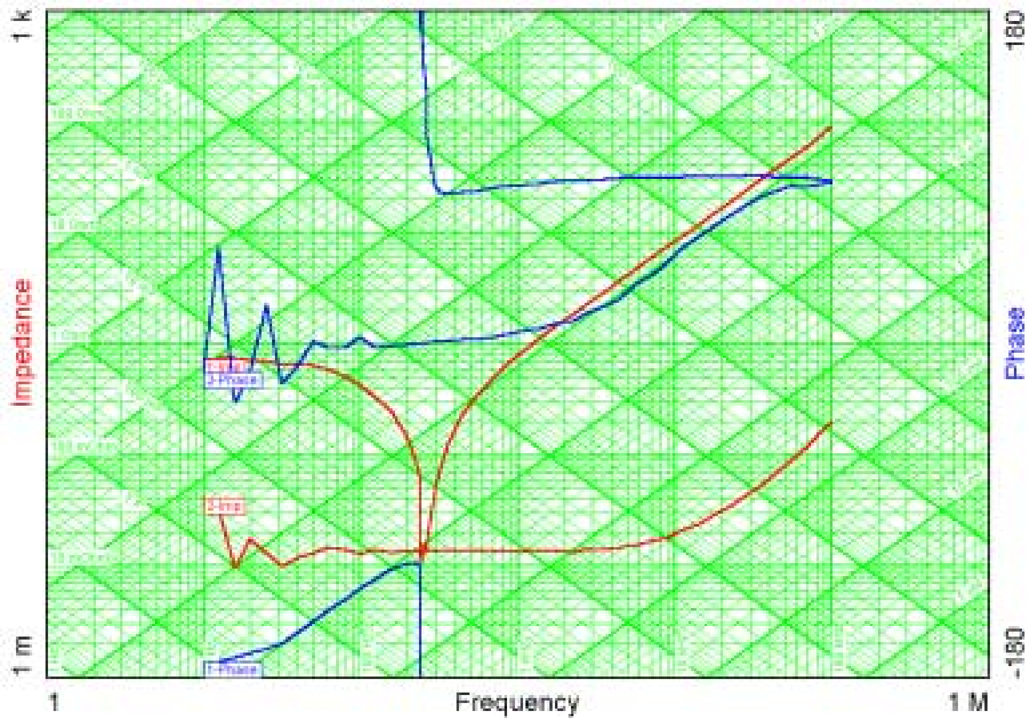


Figure 10. Oscillating system 1

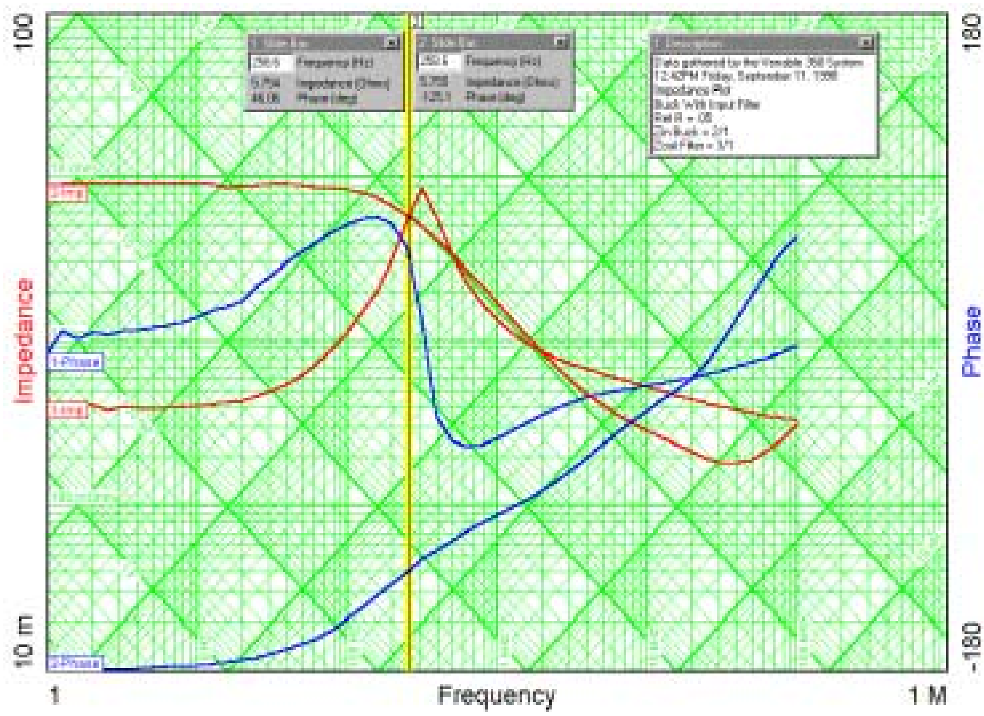


Figure 11. Oscillating system 2

Avoiding the Problem

The first suggestion is to test the impedance of each piece of the system using a frequency response analyzer and visually inspect the curves. You can inspect the source and load individually or you can combine them.

The easiest analysis is to mathematically add the source and load impedances together and inspect the combined impedance. You must have software that allows you to add impedances, but you only have to look at one graph. If the combined impedance goes close to zero, you have a problem.

If you choose to inspect them individually, see if the magnitude of the impedances ever come close or cross. If this occurs, look at the phases. If the phases are almost opposite (180° different) you may have a problem. If the magnitudes of the impedances cross when the phases are 180° different, you definitely have a problem.

Naturally, you want to test all the possible configurations and all the load states of the system. Often a system will oscillate only at high or low load. As components age the curves will change, so plan ahead and give some margin to the above criterion.