Investigation about how to drive a double resonance Tesla coil

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A double resonance Tesla coil can be designed for optimal efficiency in the way described in http://www.coe.ufrj.br/~acmq/tesla/drsstc.html

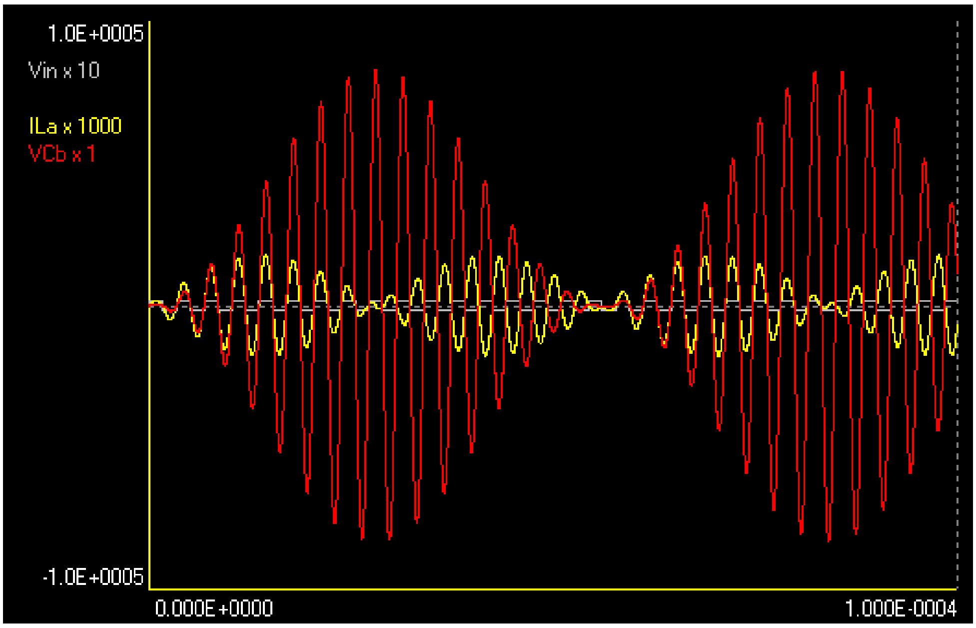
The design procedure aims to produce waveforms with complete beats, similar to the ones of a regular Tesla coil, but involving three frequencies instead of two. The design is based in the "mode", that is the ratio of the three frequencies present on the waveforms. The primary circuit has capacitance and inductance Ca, La. The secondary circuit has Cb, Lb. The coupling coefficient between La and Lb is kab. The coupling coefficient is fixed by the mode. Three of the four elements can be arbitrarily chosen.

Consider the design with:

Mode: 31:33:35
Ca= 5.0700000000 nF
La= 58.6991846863 uH
Cb= 10.4000000000 pF
Lb= 28.2000000000 mH
kab= 0.1205497549

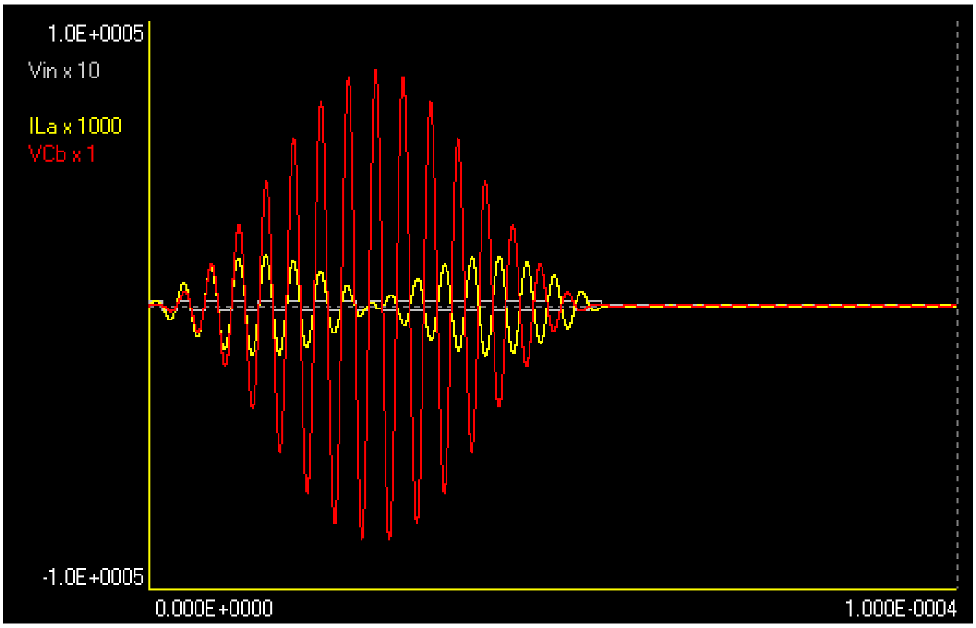
The voltage transfer function of this circuit has imaginary poles at 276583 Hz and 312271 Hz. The ideal excitation is exactly between the poles, at 294427 Hz. A feedback system set to produce zero-current switching also results in this frequency.

Without load, excitation by a continuous square wave with 180 V of amplitude results in:



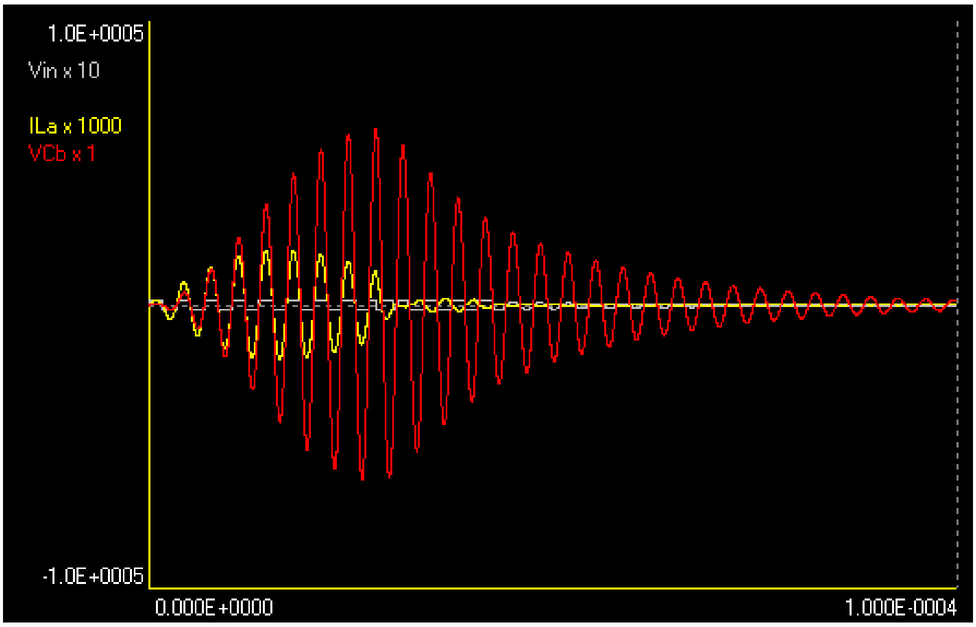
When the secondary voltage reaches its maximum value of 83 kV, at 28 us, there is no energy stored anywhere in the circuit, except in the output capacitance. The energy is then removed from the circuit and returned to the power supply, and the cycle is repeated. The maximum input current is 17.6 A, with perfect zero-current switching.

The driver can be disconnected (leaving free-wheeling diodes) at 28 us (8.25 cycles), resulting in:



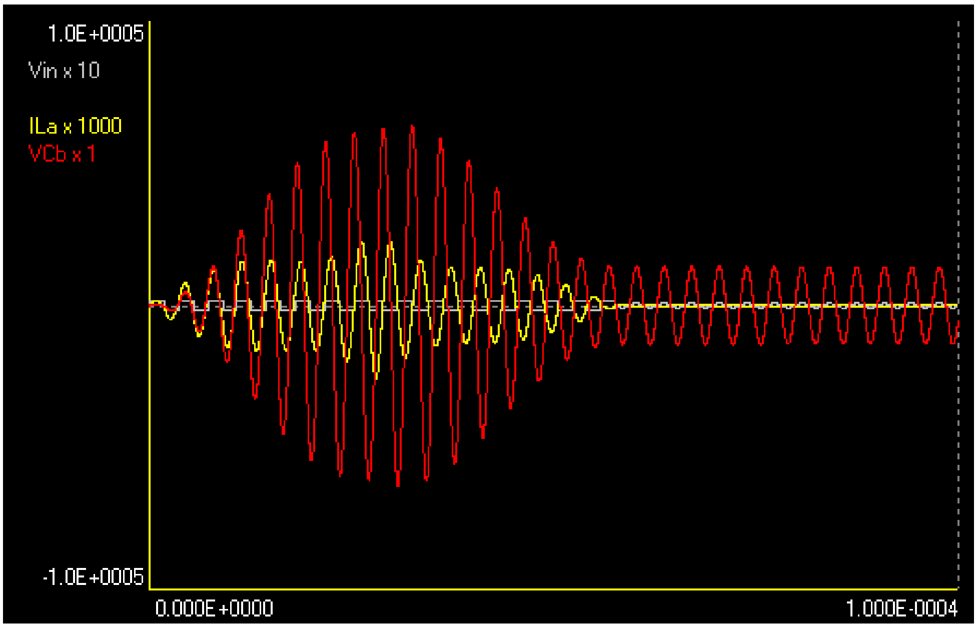
After the maximum output voltage, all the energy is removed and returned to the power supply. The small residue left is because the system was designed assuming sinusoidal excitation, and not a square wave.

Adding a load resistance of 1 MΩ, also with the 28 us burst, the waveforms change to:



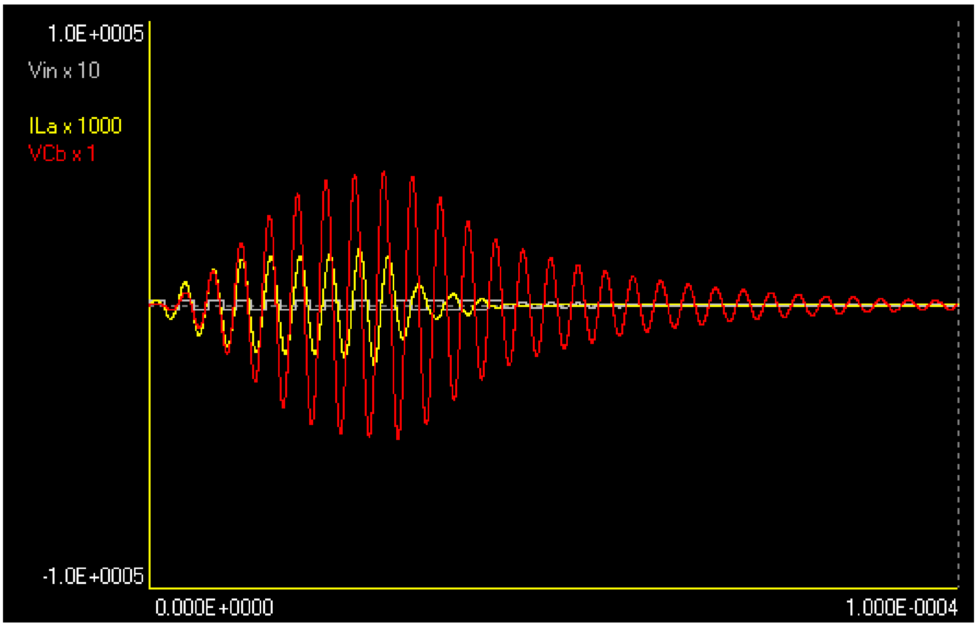
The maximum voltage drops to 62.5 kV, and the maximum input current rises to 19.5 A. The zero-current switching persists.

If the system is excited at the lower pole, 276583 Hz, also with a 28 us burst, the result without load is:



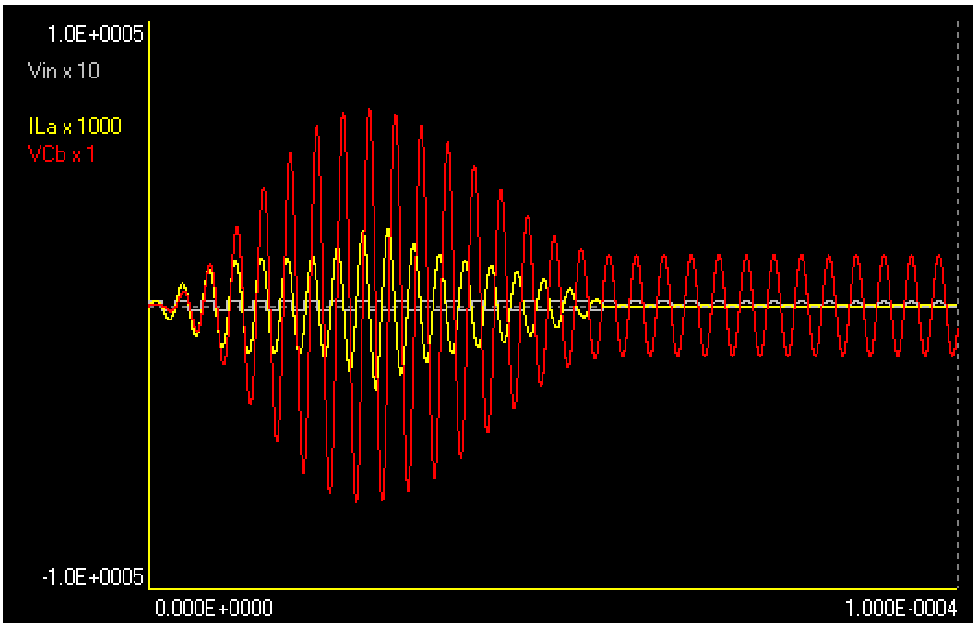
The output voltage rises more slowly, but would grow without limit if the burst does not end. The input current would also rise without limit. Zero-current switching is imperfect in the first cycles. The maximum voltage drops to 63.4 kV, and the maximum input current rises to 26 A.

With 1 MΩ load, the result is:



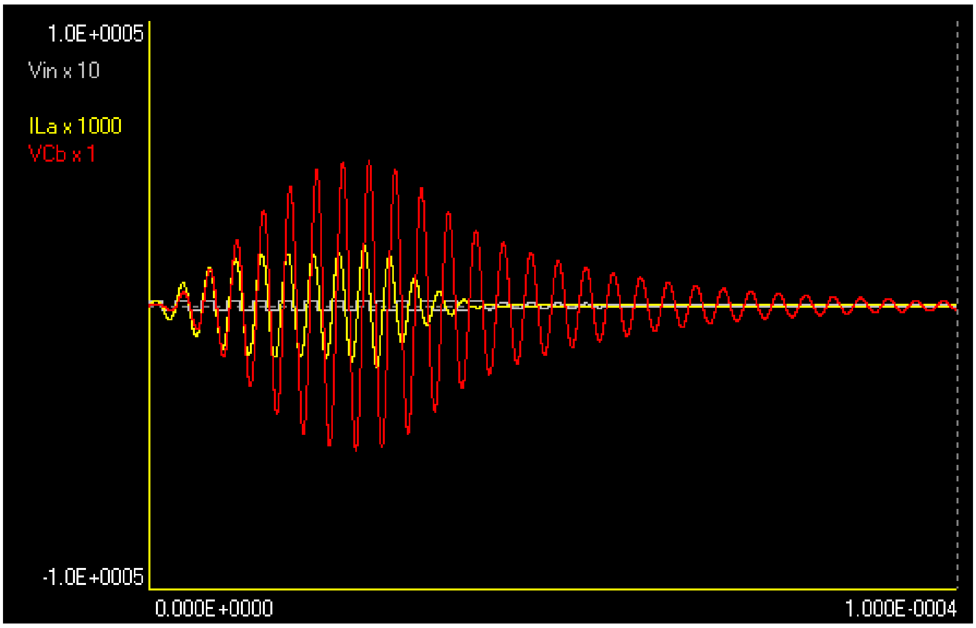
Maximum voltage: 47 kV. Maximum input current: 21.1 A. Imperfect zero-current switching.

Excitation at the upper pole, 312271 Hz, results in something similar, with slightly faster rise. Without load:



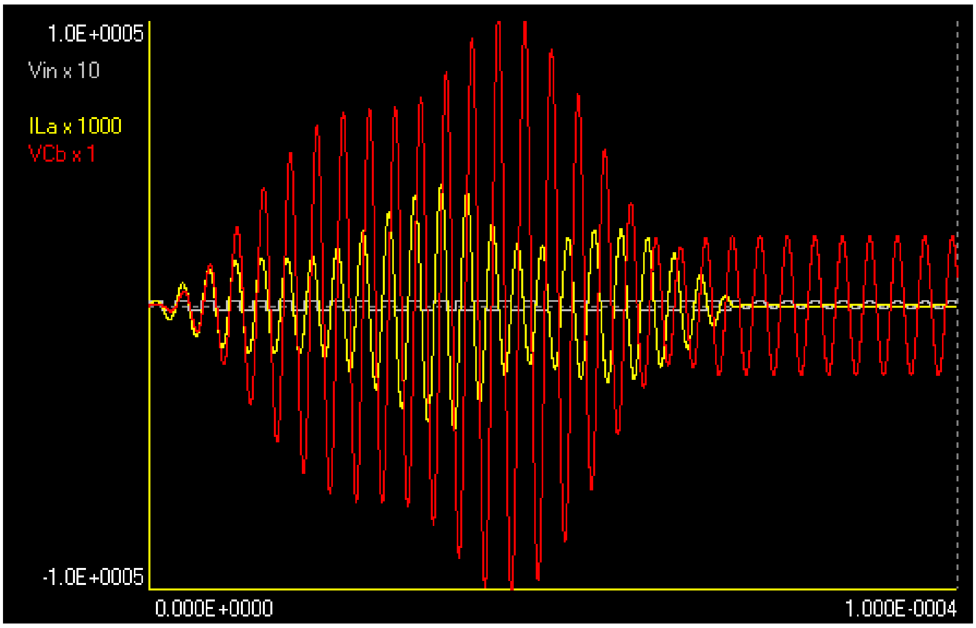
Maximum output voltage: 69 kV. Maximum input current: 29 A. Imperfect zero-current switching.

With 1 MΩ load:



Maximum output voltage: 50.8 kV. Maximum input current: 21.7 A. Imperfect zero-current switching.

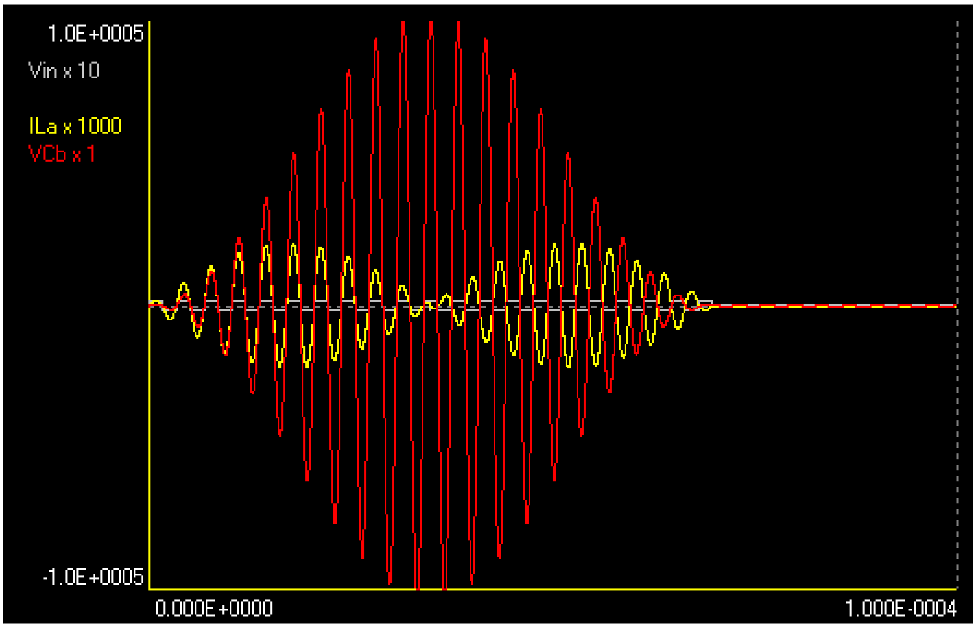
With excitation at the poles, higher voltage can be obtained by simply operating the driver for more cycles. But it is always possible to redesign the system for excitation at the central frequency and obtain the same result with greater efficiency. For example, with excitation at the higher pole and a 38 us burst, without load, the output voltage reaches 102 kV, but at the expense of 44 A at the input:



Redesigning the system to mode 39:41:43, the element values are:

Ca=   5.0700000000 nF
La= 58.3980551351 uH
Cb= 10.4000000000 pF
Lb= 28.2000000000 mH
kab=   0.0972146042

The system reaches 103.5 kV at 34.8 us, with a maximum input current of just 21.9 A:

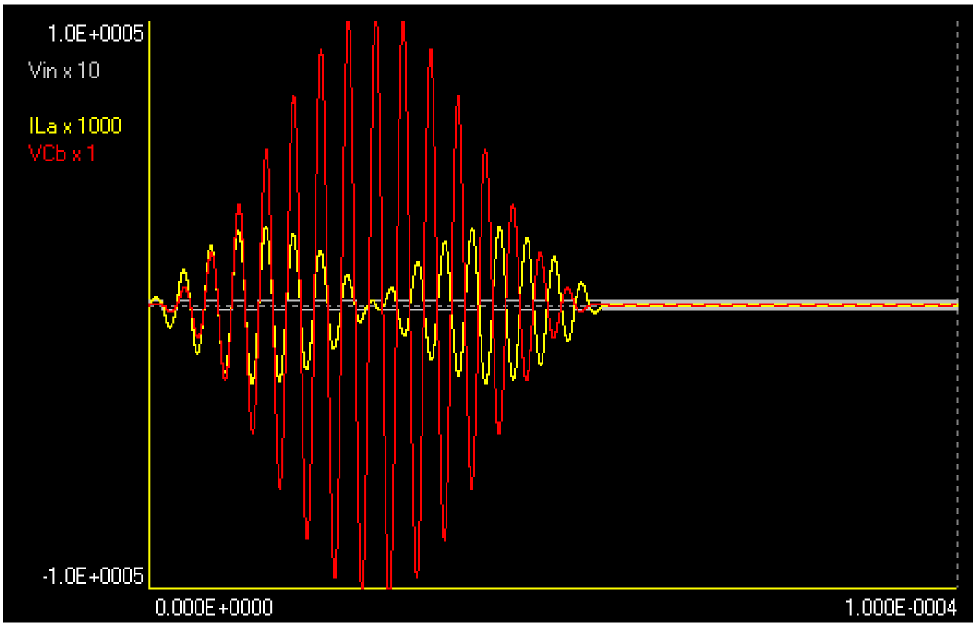


If the required coupling coefficient is too small, turning tuning excessively critical, the input capacitor can be increased. Keeping mode 31:33:35 and increasing Ca to 8 nF results in:

Ca=   8.0000000000 nF
La= 37.2006082949 uH
Cb= 10.4000000000 pF

Lb= 28.2000000000 mH
kab= 0.1205497549

The system now reaches 104.6 kV in 28 us with just 27.8 A at the input.



Conclusions:

The design for excitation at the center, between the two poles, always results in less input current for the same maximum output voltage and same time to reach it, when compared with excitation at the poles.
The use of feedback controlled by the input current leads naturally to operation at this mode, if the system is properly designed and streamer loading is light.
The system cannot be forced to greater output voltage in this case. If the burst length is increased beyond the necessary for complete energy transfer, the waveforms just repeat in the lossless case. It is still possible to reduce the output voltage by reducing the number of cycles.
With resistive load, longer burst transfer more energy to the load, but without great increase in the input current. The circuit operates in a way similar to an impedance-matching network.

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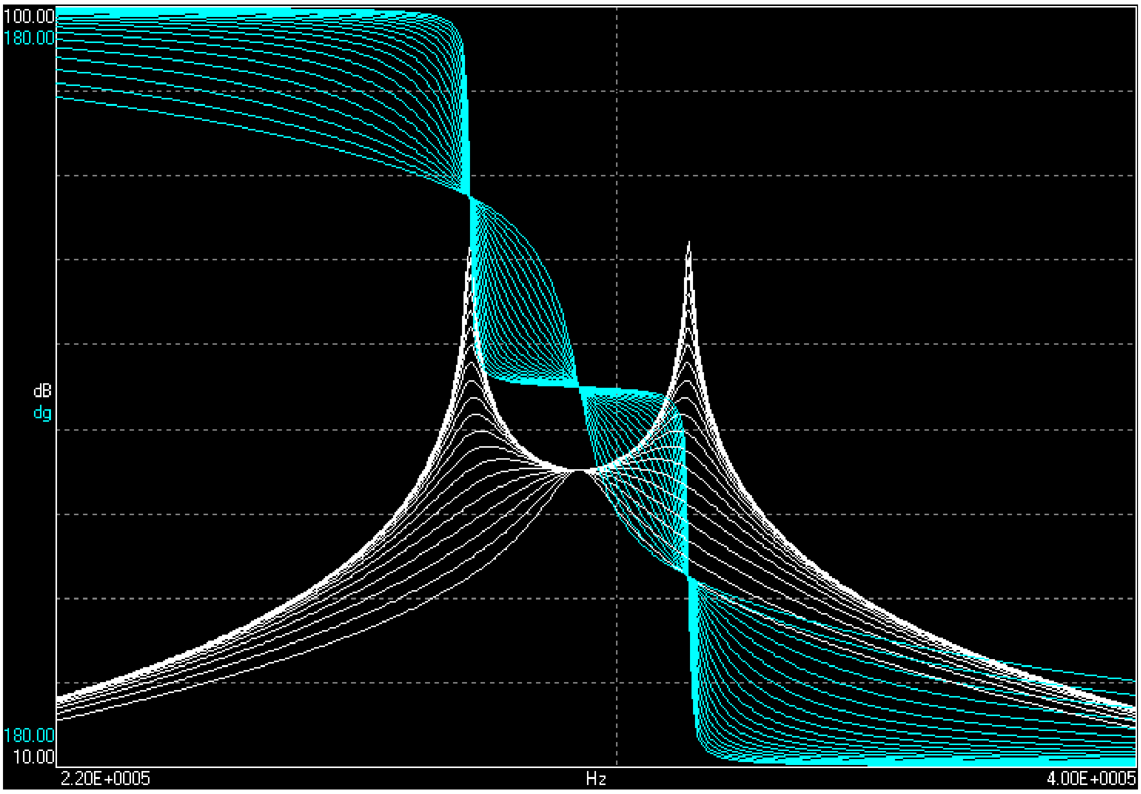
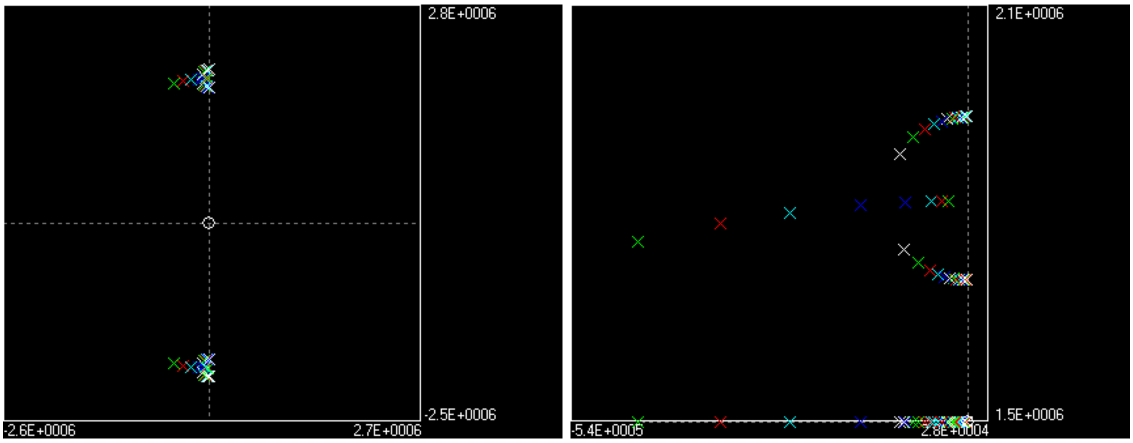
Effect of the load on the voltage transfer function and on the input impedance

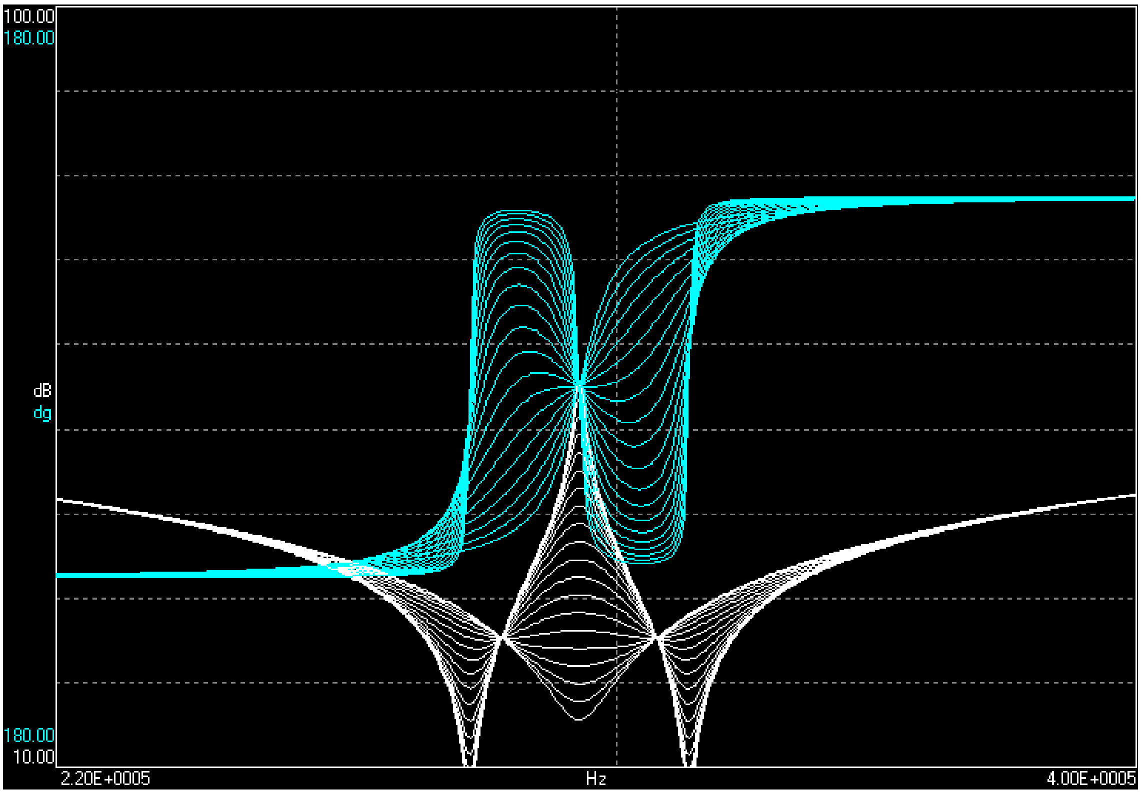
Some interesting effects appear when the resistive load of the system is varied. Considering the same circuit of the first example above, the picture below shows what happens with the voltage transfer function of the system when the load resistance is varied from 10 MΩ to 100 kΩ, in 20 steps with logarithmic spacing. The next picture shows the position of the poles and zeros of the transfer function, detailing the poles with positive imaginary part. It is seen that the poles, that initially are separated and almost imaginary, move to the same complex frequency, and then split into poles with the same modulus and different quality factors. The load resistance that creates a pair of identical complex poles is 214404 ohms. Well before this point, the frequency response starts to shows a single maximum.





Doing the same for the input impedance, the next curve shows the result for the frequency response (the modulus of the input impedance is in decibels too). With light load, the input impedance has two minima at the two maxima of the voltage transfer function and a maximum at the central frequency. It is resistive at the central frequency and almost resistive at the lateral frequencies too. As the load resistance decreases, the impedances at the lateral frequencies become more reactive, while the impedance at the central frequency remains resistive. When the load reaches about 440 kΩ, the phases around the central frequency change polarity. Note that this is not the same load that causes a single peak at the voltage transfer function. Two peaks are still present when this happens, and there is nothing special about the configuration of the poles and zeros.

What would be the consequences of this phase reversion for a control system that tries to keep the driver switching at a frequency where the input impedance is resistive? A PLL system would become unstable. A control using just a comparator to keep the voltage drive with the same polarity of the input current, turned on after a few cycles, could work correctly.



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Updates:
14/2/2013: Effects of the load in the frequency domain.
3/2/2014: Small improvements in the text.
27/11/14. Modes corrected. Small corrections.