The Resistive Capacitor

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It isn't what we don't know that gives us trouble, it's what we know that ain't so. – Will Rogers

A component is not perfect, and has parasitic features. The standard model for an inductor *L* and for a capacitor *C* is a series *L C R*. They then both self resonate at a frequency given by $\omega = 1/\sqrt{LC}$, when the impedance of the *L*, ωL, and the *C*, $1/\omega C$ are equal and so cancel. This is an elegant and beautiful idea, but unfortunately untrue.

In *Wireless World* in December 1978, we published; " .... we can recognize [a capacitor as] a parallel plate transmission line ...." [1]. The cost to the world of ignoring this information for 34 years has been high, both financially and in general comprehension.

A capacitor is made up of two parallel plates, which means it is a transmission line as is a $50\,\Omega$ coaxial cable except that the two conductors are flat rectangles, instead of concentric. In the same way as the transient, or initial, impedance of a coaxial cable is a resistive $50\,\Omega$ however it is terminated, so the transient impedance of a capacitor is resistive. However, its dimensions and dielectric constant ε_r are very different from those of a coaxial cable. They make the Z_0 of a capacitor $Z_0 = \sqrt{\mu/\varepsilon}\,(b/a)$ very small indeed, particularly for large μF values; perhaps $0.1\,\Omega$ for a $1\,\mu$F capacitor. Having an extremely high ε_r, the reduced velocity from end to end of a capacitor $1/\sqrt{\mu\varepsilon}$ means the end-to-end delay is far longer than one would expect. With an ε_r of 10,000, a capacitor one tenth of an inch long behaves like a one foot long transmission line with vacuum dielectric, whose $\varepsilon_r = 1$. Thus, the capacitor's initial transient impedance of $0.1\,\Omega$ lasts for a considerable time, and longer for a capacitor of greater value, one with a value in μF (and so with greater ε_r) rather than in pF.

In a digital system, switching logic gates make a sudden demand for charge from the local 5v power supply. Initially this is supplied by the energy in the charged grids or planes of 0v and 5v conductors, as discussed in my 1967 IEEE paper, now at [2]. What matters after this is the transient response of the local decoupling capacitor. The transient impedance of a $1\,\mu$F capacitor is perhaps $0.1\,\Omega$, in which case a sudden demand by a number of local logic gates for 100ma in the first 1nsec will cause the 5v supply to drop instantaneously by only 100mv. If the capacitor is three inches away from the sudden demand on a printed circuit board, it will begin to deliver to the new load after 1nsec. Prior to that, the initial energy will be taken from either the charged up 0v and 5v voltage planes or in the voltage grid situated between the switching logic and the capacitor. The planes or grid have an energy store which is instantaneously available, lasting for the short time until the capacitor begins to deliver 1 nsec later.

An imperfect capacitor is still called a capacitor, or can be. An imperfect transmission line is still called a transmission line, or can be. At stake is the proper use of decoupling capacitors in digital systems, and also perhaps in analogue systems. A digital system particularly needs good decoupling transient response. As the logic gate switches, the 5v supply must not collapse, as it would if the decoupling capacitor had series inductance. What happens later will sort itself out. In 1965, if a capacitor did not have initially merely resistive, not reactive, impedance (which in truth, in the case of a large value $1\,\mu$F capacitor is less than $0.1\,\Omega$), we could not have continued to increase the speed of logic because we could not have kept a stable enough 5v supply. The series inductance and "self resonant frequency" touted for capacitors would mean an end to increased speeds in the 1960s. This inductance did not exist, so we successfully continued to reduce the switching speed of logic below 1 nsec.

Use of the value of "self resonant frequency" was particularly pernicious because it drove people to use the less appropriate low value capacitors. The formula for self resonant frequency $\omega = 1/\sqrt{LC}$ tells us that the lower, worse the value of *C* in Farads, the better, higher, self resonant frequency, even though the *L*, the real problem, the legs on the capacitor, remains the same.

The key point about a transmission line is that its initial impedance is resistive, not reactive. The same applies to a properly constructed capacitor, one without long legs. A capacitor's transient impedance is resistive, not reactive. This is because it is a transmission line.

For years, Google has put me close to the top of its 300,000 hits for "self resonant frequency" + capacitor. Every time I went to Wikipedia's entry and added a hyperlink to my page, my page asserting that it does not exist, it was swiftly removed. Now, Wikipedia has removed its own entry for "self resonant frequency"! Wikipedia no longer even discusses the self resonant frequency of an inductor.

The conservatism and censorship in our industry extends beyond the protectionism of professors and text book writers defending their lecture notes and text books from destruction. It also extends to apparently minor matters like the question of whether a capacitor has a self resonant frequency, which does not threaten entrenched professors or text book writers. Earlier, giving reason for removal of the hyperlink to my site on self resonant frequency, Wikipedia said my page was "self serving and inflammatory". A more open profession and industry would be much more profitable.

References

[1] Ivor Cat, M. F. Davidson, D. S. Walton, "Displacement Current, and How to Get Rid of It", *Wirelesss World*, pp. 51-52 (Dec 1978).

[2] Ivor Catt, "Crosstalk (noise) in Digital Systems", *IEEE Trans. Electron. Comput.* **EC-16**: 743-763 (Dec 1967).