Power Supply Decoupling

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This file should provide the basics for exercise 3 of the mandatory task 1 of IN5230 and it is a summary of Chapter 5 of "Electromagnetic Compatibility" by Henry W. Ott.

Motivation

Power supply decoupling should reduce the effect of one IC to another and provide a low impedance path between power and ground. When a logic gate switches, current transients are produced and they can affect the power voltage. Therefore, capacitors are used to reduce the fluctuation of power supply due to digital circuits, as they *absorb* current transients (see Fig. 1).
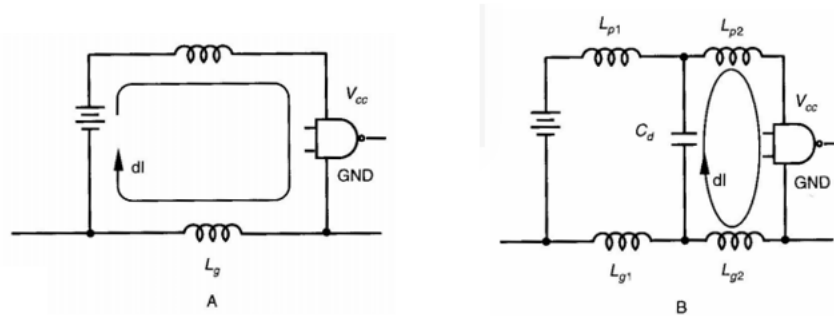

Figure 1: (A) Logic gate and transient current dI generated by gate switching. (B) effect of decoupling capacitor.

The current transients produce harmonics in the power spectrum, whose frequeuncies depend on the rising/falling time, as well as the current period (e.g. clock cycle) as shown in Fig. 2.
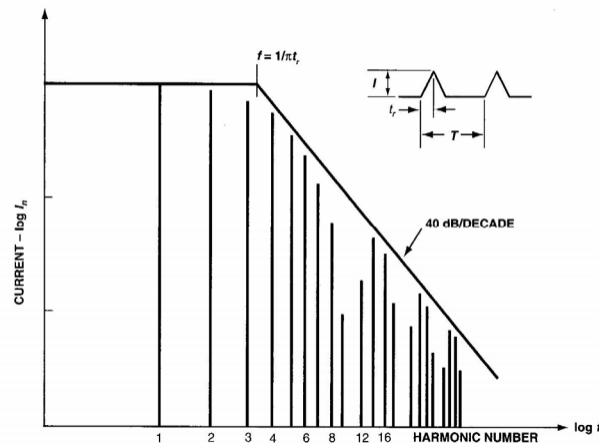

Figure 2: Fourier spectrum of the current depending on rising/falling time. Note that when f$>1/\pi t_r$ the current spectrum falls as 40 dB/decade.

Decoupling capacitors

While ideally capacitors are *purely capacitive*, in reality they also have an inductance (due to the capacitor itself, the PCB traces, and the IC leads). Therefore, connecting a decoupling capacitor results in an equivalent circuit shown in Fig. 3.
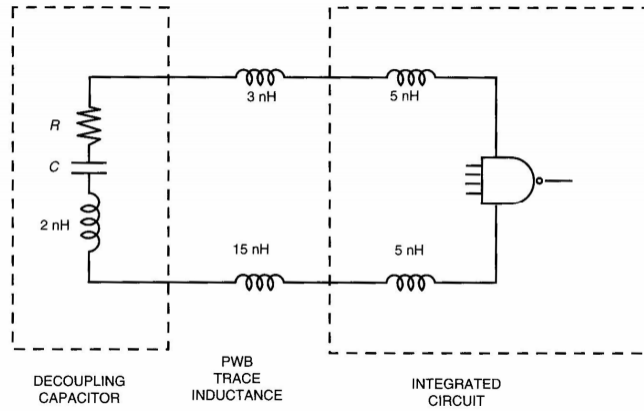

Figure 3: Equivalent circuit for decoupling capacitor.

The decoupling network is therefore a series of resonant circuits. **We are effectively placing an L-C network between power and ground, not only a capacitor!**

The resonant frequency of the LC network is:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

At the resonant frequency the impedance is very low, while it increases below and above the resonant frequency. Fig. 4 shows the frequency-dependent impedance for typical values of L and C used in PCB design. The plot shows that typical values for a single capacitor are not able to decouple digital logic circuits for frequencies above 50 MHz.
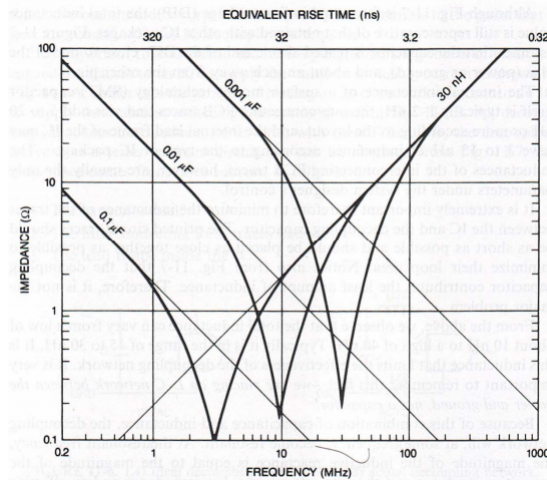

Figure 4: The frequency-dependent impedance of the LC network shows a resonant behavior.

Effective decoupling strategies

The contamination of the power supply might be reduced by:

1. Slow down rise time

2. Decrease current transient

3. Decrease series inductance

4. USE MULTIPLE CAPACITORS

While 1. and 2. will likely get worse with advances in technology and 3. can only be limited to a certain amount, the best way to improve decoupling is tu use multiple capacitors, both to teduce the impedance and increase the frequency range.

When we use L-C networks of the same value in patrallel:

$$C_{tot} = nC$$

$$L_{tot} = \frac{L}{n}$$

(only if mutual inductances are negligible).

Increasing the number of parallel capacitors, by keeping the same total capacitance, effectively reduces the impedance and increases the resonant frequency (see Fig. 5). In practice, you should use multiple capacitors in parallel and spread them out to avoid mutual inductances between their *inductive* behavior.
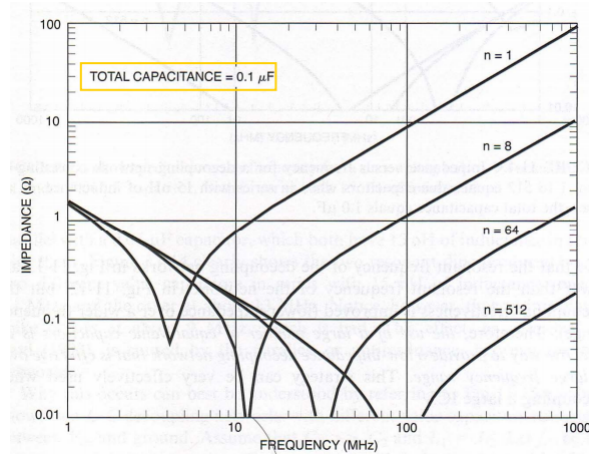

Figure 5: The frequency-dependent impedance of the n parallel LC circuits. The impedance is reduced and the resonant frequency is increased as n increases.

The use of a large number of equal value capacitors is an effective way to provide a low-impedance decoupling network that is effective over a large frequency range.

Target impedance

For an effective decoupling, the impedance must be kept below a certain target for the range of frequencies of interest (target impedance, see Fig. 6). From Fig. 2, we know that for frequencies greater than $1/\pi t_r$ the harmonics amplitude falls at 40 dB/decade. Therefore, it is enough to provide a low target impedance up to $f_h = 1/\pi t_r$,

since for larger frequencies the impedance increases at 20 dB/decade, but the noise contirbution decreases at 40 dB/decade. Using this simple formula, one can estimate the number of required capacitors:

$$n = \frac{2L}{Z_t t_r}$$

where L is the inductance of each capacitor, t_r is the rising time, and Z_t is the low frequency target impedance.
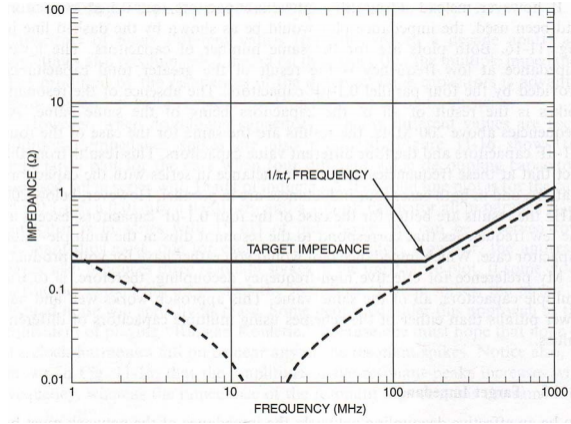

Figure 6: Target impedance (solid line) and impedance of decoupling network (dashed line). Note that the impedance of the LC network is below the target impedance for the frequencies of interest.

In order to identify the target impedance Z_t, we can use the amount of allowed variation in the power supply (dV) given a certain amplitude of the transient current (dI). Then:

$$Z_t = k\frac{dV}{dI}$$

where k is a correction factor that accounts for the amount of power contained below and above the high frequency $f_h = 1/\pi t_r$ (from Fig. 2, only about 50% of the current power is below f_h, therefore the target impedance can be increased by $k = 2$).