Updating Circuit Theory: Power Line Filter

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Introduction

A filter is described which absorbs transient energy in the supply line as well as minimising the effect of those transients on the load. Traditional filters simply reflect that energy back into the line where the only place for it to go is into the environment. This manifests itself as cross-coupled interference as well as radiated interference.

A model is created which simulates the interaction between the filter and the supply line. It is shown that the device performs its intended function in protecting the load and in preventing load transients from reaching the line. It also absorbs any transient energy, whatever the source. Any system which includes such filters will experience much reduced levels of EMI.

Basic Power Line

At least two conductors are involved in routing power from one location in a system to another; the send conductor and the return conductor. Figure 1 provides a schematic diagram of such a link. At the near end, the battery simulates a DC source of power, the 0.1 ohm resistor simulates the source impedance, and SW1 is initially open. The line itself is 15 m long. The load at the far end is a 10 ohm resistor in series with an isolating switch, SW2, which is initially closed.

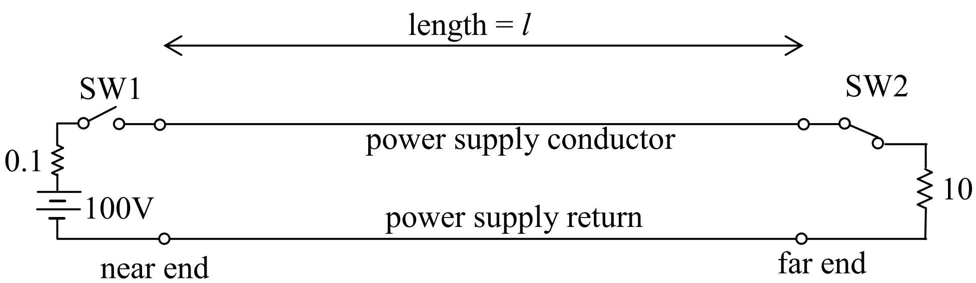

Figure 1 wiring assembly of power supply line

The response of the line can be simulated using the technique described in the article ‘Updating Circuit Theory: Power Line Transients’. If it is assumed that SW1 closes at the start of the simulation and SW2 opens after 10 micro-seconds, then the waveform of the current at the near end of the line would be as illustrated by Figure 2.

At switch-on, the current rises in a series of small steps to settle at a steady 10 A. The shape on the curve is that of an L-R series circuit; the inductance of the line in series with the 10 ohm load.

When the load is switched off, the energy stored in the line is trapped by a short circuit at the near end and an open circuit at the far end. So current oscillates back and forth. If the velocity of propagation v is 300 metre/micro-second, then the time T for a single traverse is

$$T = \frac{l}{v} = 50\,\text{ns} \tag{1}$$

Since it takes four traverses of a signal to complete a cycle, the frequency f is

$$f = \frac{1}{4 \cdot T} = 5\,\text{MHz} \tag{2}$$

If there were no radiation losses, then a 5 MHz square wave would exist on the line, decaying slowly due to energy losses in the 100 milli-om resistance at the near end. However, each conductor acts as an antenna, and current emanates from the line in the form of a burst of radiation. This is illustrated by the response following the switch-off at 10 micro-seconds.

There is no doubt that this energy will depart into the environment in the form of electromagnetic interference.

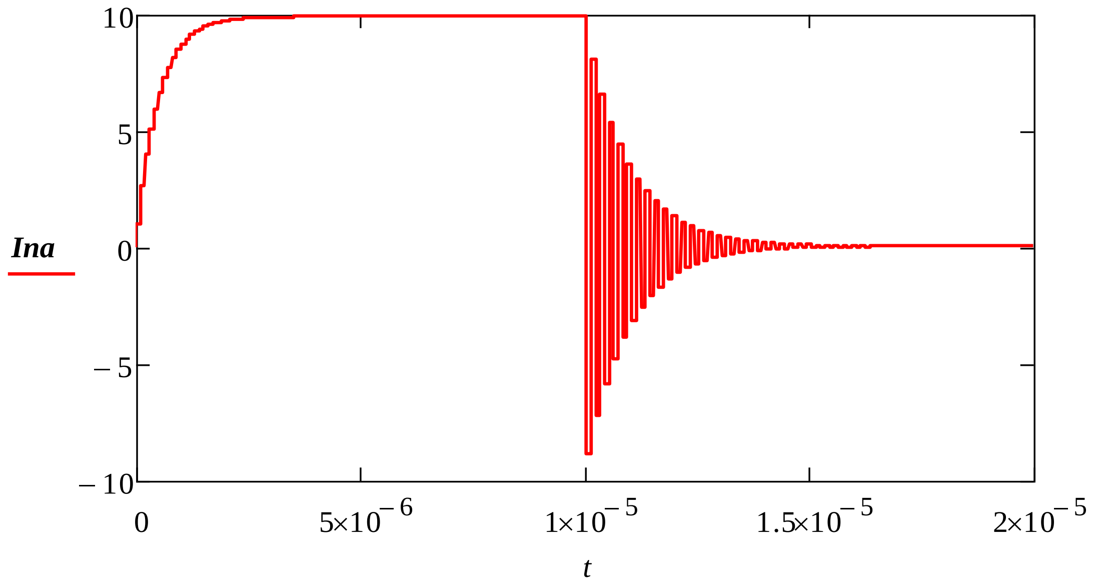

Figure 2 Waveform of current in power line.

Adding a Filter

This ringing pulse can be eliminated by the filter circuit of Figure 3. This assembly differs from conventional power line filters in that it includes resistive components. There is a resistor in parallel with each inductor and a resistor in series with the capacitor.

Under steady-state conditions, the inductor provides zero impedance and the capacitor acts as an open-circuit. So the current delivered to a 10 ohm resistor at the far end by a 100 V source at the near end is just less than 10 A.

When a transient step arrives at the far end, the inductors present a high value of impedance and the capacitor provides zero impedance. So the load at this end is effectively two 50 ohm resistors in series. If the characteristic impedance of the line is 100 ohm, then all of the transient energy will be absorbed. There will be no reflections and no high frequency interference.

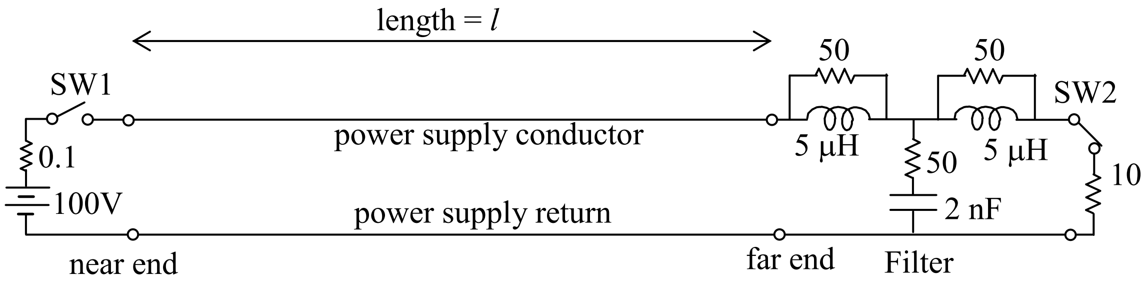

Figure 3 Wiring assembly of line and filter

Block diagram

Analysis of this power link can be divided into four functional entities; the interface circuit at the near end, the forward propagation of energy, the interface circuitry at the far end, and the propagation of energy back down the line. This is illustrated by the block diagram of Figure 4. Signal processing in each block is defined by a unique set of equations.

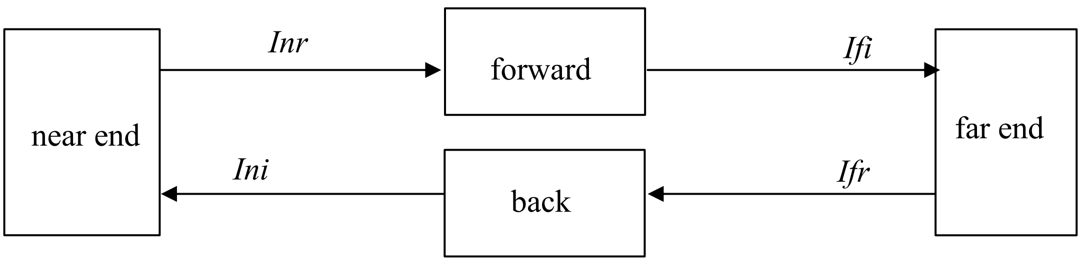

Figure 4 Block diagram, identifying signal processing functions

Near end

Equations at the near end are defined by the circuit model of Figure 5.

$$Vg + 2 \cdot Ro \cdot Ini = (Ro + Rn) \cdot Ina \qquad (3)$$

This leads to

$$Ina = \frac{Vg + 2 \cdot Ro \cdot Ini}{Ro + Rn} \qquad (4)$$

Since the current *Ina* at the near end is defined as the sum of the incident and reflected currents, the value of the reflected current is:

$$Inr = Ina - Ini \qquad (5)$$

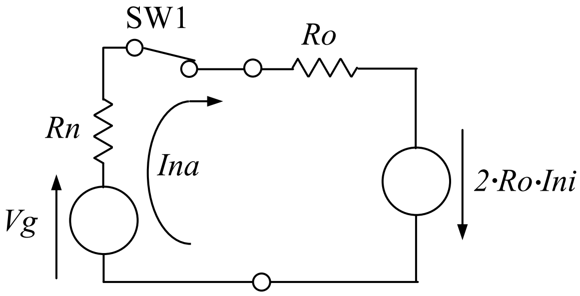

Figure 5 Circuit model of interface at the near end

Transmission Line

For transient analysis, any transmission line can be defined by two parameters, the characteristic resistance *Ro* and the time *T* it takes a signal to propagate from one end to the other. It is assumed that the line is lossless, so

$$Ro = \sqrt{\frac{L}{C}} \tag{6}$$

Where *L* is the inductance of the loop as measured at the near end when the far end terminals are shorted together and *C* is the capacitance between the conductors when the terminals at the far end are open-circuit.

The line can be represented as two shift registers, one simulating the forward propagation of charges, the other simulating the propagation of charges back from the far end to the near end. Details of the software used to carry out this simulation are provided by the article ‘Updating Circuit Theory: Charges and Photons’.

Far end

Equations at the far end are defined by the model of Figure 6. There are four circuit loops. So there are four mesh equations.

$$2 \cdot Ro \cdot Ifi = (Ro + R1 + R2) \cdot Ifa + \frac{Qfa}{C1} - \frac{Qfc}{C1} - R1 \cdot Ifb - R2 \cdot Ifc \tag{7}$$

$$0 = -R1 \cdot Ifa + R1 \cdot Ifb + L1 \cdot \frac{dIfb}{dt} \tag{8}$$

$$0 = -\frac{Qfa}{C1} - R2 \cdot Ifa + \frac{Qfc}{C1} - (R2 + R3 + R4) \cdot Ifa - R3 \cdot Ifd \tag{9}$$

$$0 = -R3 \cdot Ifc + R3 \cdot Ifd + L2 \cdot \frac{dIfd}{dt} \tag{10}$$

Let $$Qf = (Qfa - Qfc) = (Ifa - Ifc) \cdot dt \tag{11}$$

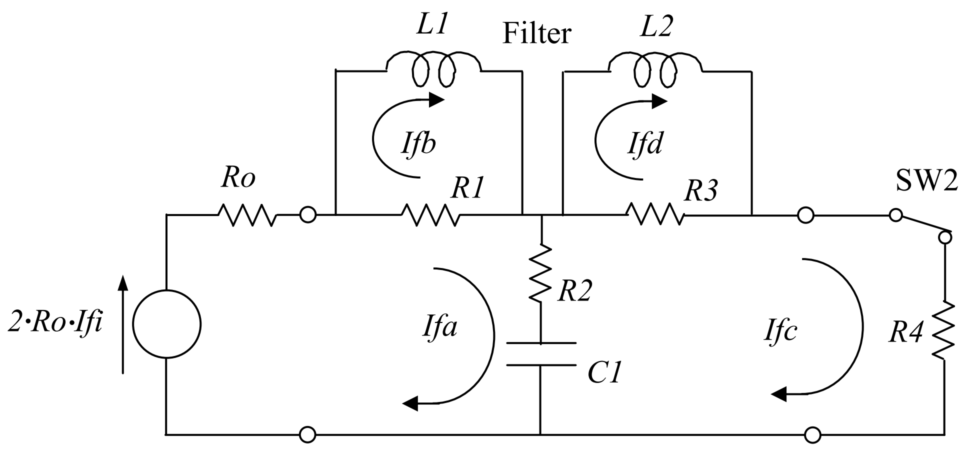

Figure 6 Circuit model of the interface at the far end; filter, switch and load

First page of worksheet

Having defined the equations associated with each block of Figure 4, there is now enough information to allow a Mathcad worksheet to be compiled. The two pages are replicated by Figures 7 and 8.

The first two lines of Figure 7 assign values to the parameters of the circuit models of Figures 5 and 6 using the components defined by Figure 3. The third line defines the values used in the simulation of the cable link. The fourth line defines the time *Toff* when SW2 opens.

The function *near* ( ) is derived from equations (4) and (5).

The functions *forward* ( ) and *back* ( ) are copied from Figure 5 of the article 'Updating Circuit Theory: Charges and Photons'. Each simulates the actions of a shift register.

The function *far* ( ) is derived from equations (7) to (11).

Second page of worksheet

This page defines the main program and creates a graph which simulates the waveform of the current *Ina* at the near end of the line. Figure 8 is a copy of the text.

The number *N* defines the number of transits of the leading edge of the waveform along the line. Since the time taken for one transit is 50 nanoseconds, then 400 such transits takes 20 microseconds. This defines the timescale of the simulation and the time variable *t*.

The main program takes the output of each function and uses it as the input of the next function. This means that any current (*Ina, Ini, Inr, Ifi, Ifa, Ifb, Ifc, Ifd,* or *Ifr*) can be selected as the output variable. In this case, the output is *Ina*.

$Vg := 100 \quad Ro := 100 \quad Rn := 0.1 \quad R1 := 50 \quad R2 := 50 \quad R3 := R1$

$L1 := 5 \cdot 10^{-6} \quad L2 := L1 \quad C1 := 2 \cdot 10^{-9}$

$l := 15 \quad v := 3 \cdot 10^{8} \quad T := \frac{l}{v} = 5 \times 10^{-8} \quad n := 10 \quad dt := \frac{T}{n} = 5 \times 10^{-9}$

$Toff := 10 \cdot 10^{-6} \quad Noff := \frac{Toff}{dt} = 2 \times 10^{3}$

$$near(Ini, Vg) := \left| \begin{array}{l} Ina \leftarrow \dfrac{2 \cdot Ro \cdot Ini + Vg}{Ro + Rn} \\ Inr \leftarrow Ina - Ini \\ (Inr \quad Ina) \end{array} \right.$$

$$forward(\mathbf{F}, In) := \left| \begin{array}{l} \mathbf{F}_1 \leftarrow In \\ for \ \ x \in n+1 .. 1 \\ \quad \mathbf{F}_{x+1} \leftarrow \mathbf{F}_x \\ If \leftarrow \mathbf{F}_{n+2} \\ (\mathbf{F} \quad If) \end{array} \right.$$

$$back(\mathbf{B}, If) := \left| \begin{array}{l} \mathbf{B}_{n+1} \leftarrow If \\ for \ \ x \in 2 .. n+1 \\ \quad \mathbf{B}_{x-1} \leftarrow \mathbf{B}_x \\ In \leftarrow \mathbf{B}_1 \\ (\mathbf{B} \quad In) \end{array} \right.$$

$$far(Ifi, Ifa, Ifb, Ifc, Ifd, Qf, R4) := \left| \begin{array}{l} dIfb \leftarrow \dfrac{dt}{L1} \cdot R2 \cdot (Ifa - Ifb) \\ Ifb \leftarrow Ifb + dIfb \\ Ifa \leftarrow \dfrac{2 \cdot Ro \cdot Ifi - \dfrac{Qf}{C1} + R1 \cdot Ifb + R2 \cdot Ifc}{Ro + R1 + R2} \\ dIfd \leftarrow \dfrac{dt}{L2} \cdot R3 \cdot (Ifc - Ifd) \\ Ifd \leftarrow Ifd + dIfd \\ Ifc \leftarrow \dfrac{1}{R2 + R3 + R4} \left(\dfrac{Qf}{C1} + R2 \cdot Ifa + R3 \cdot Ifd \right) \\ Qf \leftarrow Qf + (Ifa - Ifc) \cdot dt \\ Ifr \leftarrow Ifa - Ifi \\ (Ifr \quad Ifa \quad Ifb \quad Ifc \quad Ifd \quad Qf) \end{array} \right.$$

Figure 7 First page of worksheet: definition of functions

$N := 400 \cdot n - 1 \qquad i := 1 .. N \qquad t_i := i \cdot dt$

$$
\mathbf{Ina} := \left|
\begin{array}{l}
\mathbf{F}_{n+2} \leftarrow 0 \\
\mathbf{B}_{n+1} \leftarrow 0 \\
R4 \leftarrow 10 \\
\text{for } i \in 1 .. N - 1 \\
\quad \left|
\begin{array}{l}
Vgen \leftarrow Vg \quad \text{if } i > 1 \\
R4 \leftarrow 10^{6} \quad \text{if } i > Noff \\
(Inr \quad Ina) \leftarrow near(Ini, Vgen) \\
(\mathbf{F} \quad Ifi) \leftarrow forward(\mathbf{F}, Inr) \\
(Ifr \quad Ifa \quad Ifb \quad Ifc \quad Ifd \quad Qf) \leftarrow far(Ifi, Ifa, Ifb, Ifc, Ifd, Qf, R4) \\
(\mathbf{B} \quad Ini) \leftarrow back(\mathbf{B}, Ifr) \\
\mathbf{mon}_i \leftarrow Ina
\end{array}
\right. \\
\mathbf{mon}
\end{array}
\right.
$$

$Vg = 100 \qquad Ro = 100 \qquad Rn = 0.1 \qquad R1 = 50 \qquad R2 = 50 \qquad L1 = 5 \times 10^{-6}$

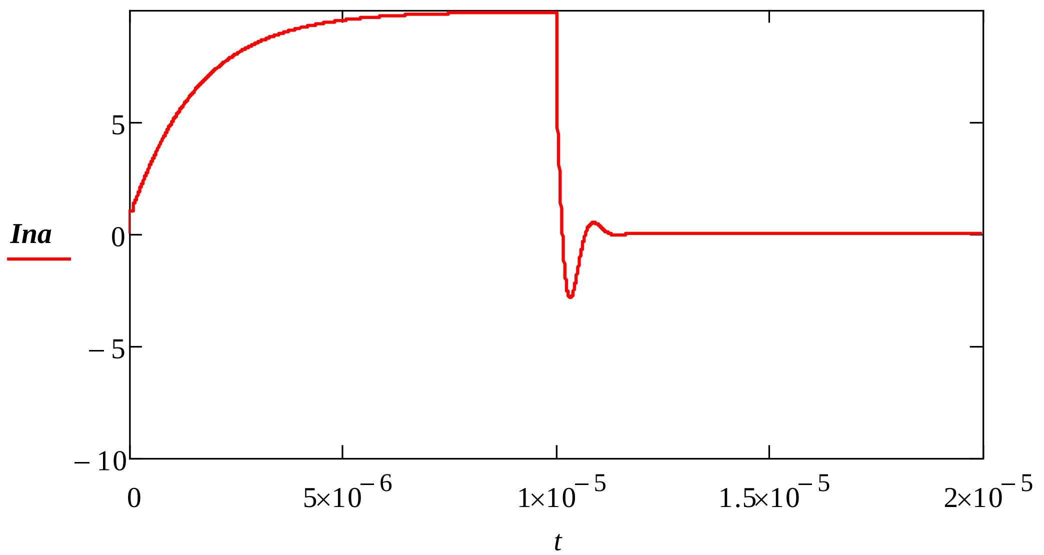

Figure 8 Second page of worksheet: main program and graph of current waveform

Conclusion

Comparing the graph of Figure 8 with the waveform of Figure 2 shows that the simple filter of Figure 6 has a dramatic effect on the EMC of the system. The high amplitude, high frequency current which occurs at switch-off has disappeared. This is the current which the cause of most of the radiated emission from the system.

The design concept is simple. Just add resistors to the L and C components to absorb high frequency energy. Select values which provide a load resistance equal to the characteristic impedance of the line, over the frequency range where radiated interference might be a problem.

At low frequencies, the filter is transparent.

Installing such filters in the electronic system could eliminate the vast majority of radiated interference problems.

The real puzzle is: why has no-one thought of this before?