TS-SSC 91-247

TECHNICAL NOTE

Date: 12/12/91
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Subject: Electrical Modelling of Magnets - Long time-scale
To: Wayne Koska

Using measurement data of magnet DCA313 and printouts of the ringing waveform (100v), an electrically equivalent model of the ringing of the magnet was developed. A circuit analysis program on the IBM PC was used to was electrically model the magnet, based on values of inductance and series resistance obtained by direct measurement of the magnet. A ring of the magnet model was then simulated, using the circuit analysis program, and compared to the actual result of ringing the magnet. Analysis was performed primarily over the long time-scale (low-frequency cycle of the wave response), although behavior of the model in the short time-scale was also examined.

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Coil Modeling of DCA313
Eric Schmitz 12/12/91

Analysis of magnet DCA313 provided results in which theoretical prediction closely matched actual data, both in terms of frequency and amplitude, over the first low-frequency cycle of the ring response. The equivalent circuit was modelled in two ways - the "Model 1" configuration used in all models "c50m1*.ckt", and a simple RLC circuit - both using directly measured values of Ls and Rs of the magnet and the known value of charging capacitor, Cs.

The values used in the model are calculated here:

Ls = 70.20mH, Qs = 2.55, both measured at 75Hz.

Using Rs = wLs/Qs, the resistance is
Rs = 2*pi*75*(70.20E-3)/2.55 = 12.97 ohms.

In other measurements (of individual coils), it was found that the inductance of the inner coil is approximately one third that of the outer coil. So, using Lin = 1/3 * Lout, we calculate:
Lin = (70.20mH)/8 = 8.78mH, and
Lout = 3/8 * (70.20mH) = 26.33mH.

Due to the layout of the circuit model, each coil is split into two equal-value inductors, so:
L1a = L1b = L4a = L4b = 1/2 * Lin = 4.39mH, and
L2a = L2b = L3a = L3b = 1/2 * Lout = 13.16mH.

Series resistance is also split up, this time into six equal-value elements for each coil. (This is necessary due to circuit analysis program syntax for modelling mutual inductance, even though no mutual inductance was included in this model. The resistances are still modelled this way for consistency.)
R1xn = R4xn = 1/6 * (2.9) = 0.49ohms, and
R2xn = R3xn = 1/6 * (3.6) = 0.6ohms. [x=a,b;n=1,2,3]

Since the measurement of Ls was a measurement of the entire magnet, the effects of mutual inductance between coils is already contained in that value. Therefore, no mutual inductance was explicitly included in the model.

The values calculated were then used in the coil model based on c50m1b, which has M=0. All other values remained the same as in c50m1b. This new model is called c50m2b.

In terms of period of oscillation, the chart produced by the modelling (Figure 1) agreed exactly with what was mathematically predicted by the equation:
f = 1/(2*pi*/Ls*C) = 75.67Hz, or T = 13.2msec.

The actual measurement of T = 13.76msec (Figure 2) differed from theoretical by 4.2%.

The much simpler RLC circuit (Figure 3) behaved exactly as the more complex model. This is not surprising. At this relatively low frequency, the effects of all coupling capacitances (coil-to-coil and coil-to-ground) have no appreciable affect, and we are left with a series network of resistances and inductances. Since L's and R's in series are additive, they simply mathematically recombine into their original total-magnet values.

It should also be pointed out here that since the voltage trace being examined is across the entire magnet, this is an acceptable approximation. In this case, it does not even matter how the L's and R's are grouped, as long as they all add up to the total inductance and resistance. Upon individual analysis of each coil, however, the grouping, including mutual inductance, does indeed matter, as shall be seen in the high-frequency analysis, next.

Results of the high-frequency analysis were not nearly as consistent between the models and the actual results. Actual values of the coupling capacitances and their associated resistances were not available, so values were essentially guessed at. (Further experimentation involving trial and error in choosing these values may eventually lead to an accurate prediction, but for now, they are simply estimates.) The resulting graph of c50m2b (Figure 4) matches the actual trace neither with respect to frequency nor with respect to amplitude. For this analysis, the model must be improved.

Comparing the graphs of models c50m1b (Figure 6) and c50m1p (Figure 7) shows that much better amplitude and frequency matching was obtained after making the changes from c50m1b to c50m1p. In the case of the new model, c50m2b, all changes were made with regard to coupling capacitances and resistances as were made between c50m1b and c50m1p. The new values of Ls and Rs were used, and the mutual inductance was left at M=0. This model is called c50m2p.

Examination of the differences between c50m1b and c50m1p reveals, for example, that the first trough of the graph of V across the upper inner coil has risen to a level of 0v in c50m1p from a value of -18v in c50m1b. The change between c50m2b and c50m2p (Figure 5) shows no such drastic change, only from -43v to -30v. It is therefore concluded that mutual inductance plays a significant role in this analysis and must be explicitly modelled as part of the model circuit structure, rather than implicitly modelled by simply dividing up the total magnet inductance. It is also important, in this high-frequency analysis, to accurately model the circuit in its divided form, since the now-substantial effect of the coupling capacitances and resistances makes this divided form necessary.

For comparison, the models c50m1b and c50m1p were also plotted on the long timescale (Figure 8 and Figure 9, respectively). Although model c50m1p somewhat accurately describes the response of the upper inner coil on the short timescale, neither model is at all accurate in the long timescale analysis. It is therefore concluded that a truly accurate model, one that describes the ringing response both in the short and long timescale analyses has yet to be developed.

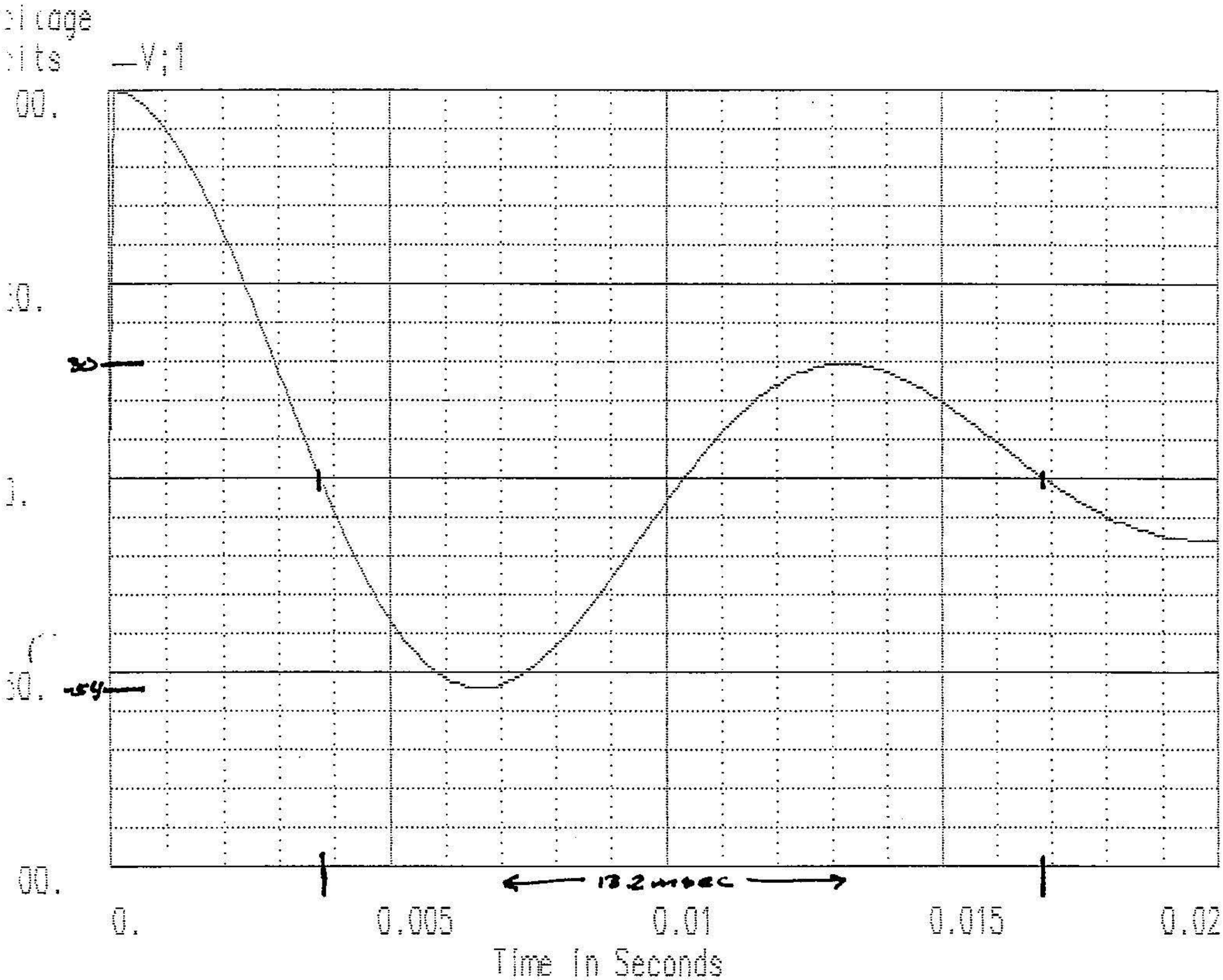

Figure 1

c50m2b.ckt

M=Ø

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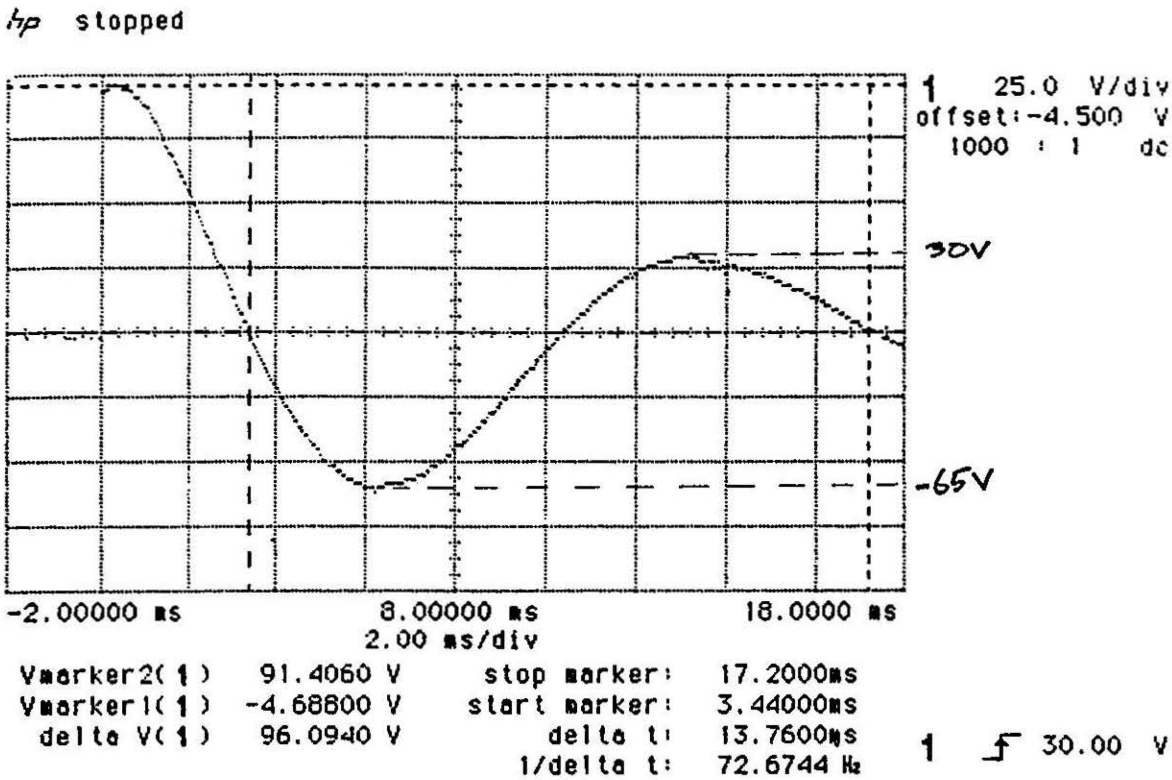
100 V



f_{PRED} : 75.67Hz ⟶ 13.2ms

f_{MEAS} : 72.67Hz ⟶ 13.76ms

Figure 2

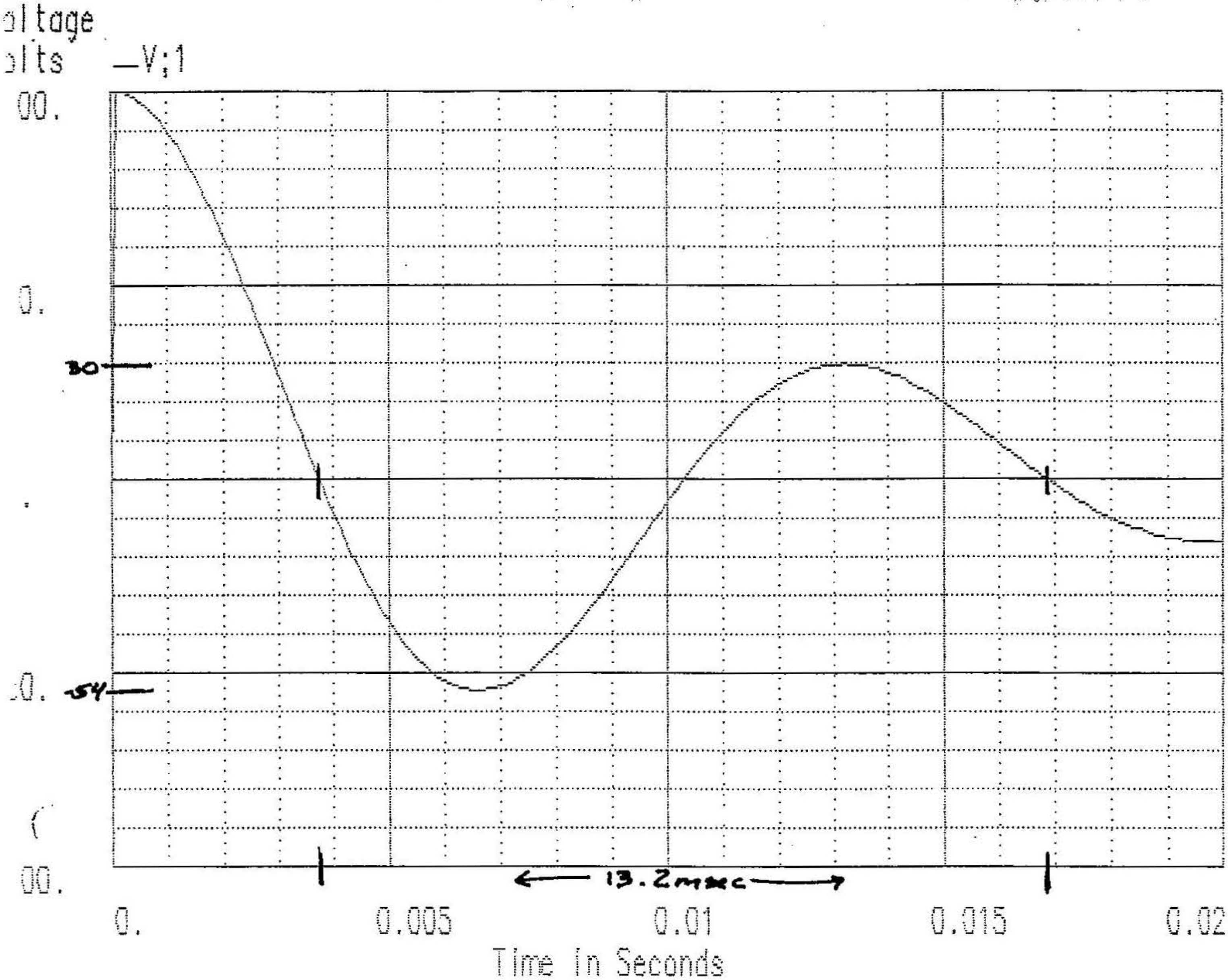
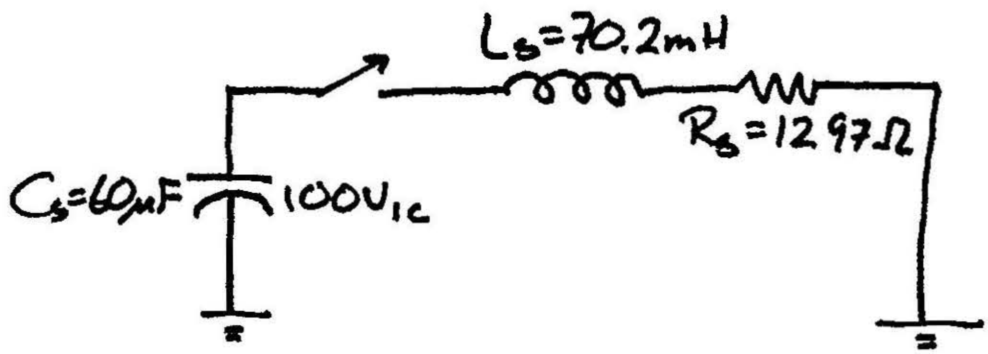


Figure 3

C50smpl1.ckt



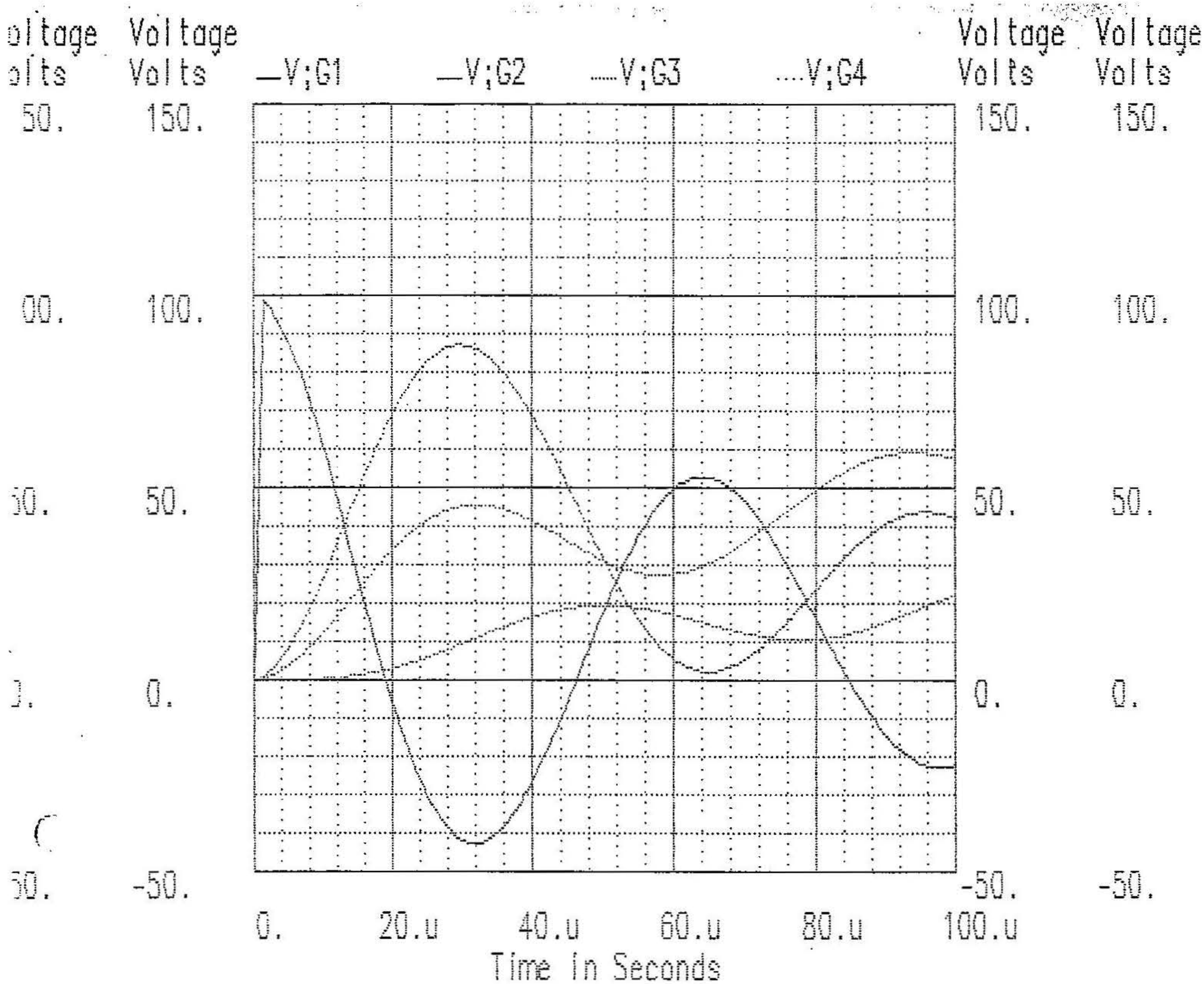


Figure 4

c50m2b.ckt

M=Ø

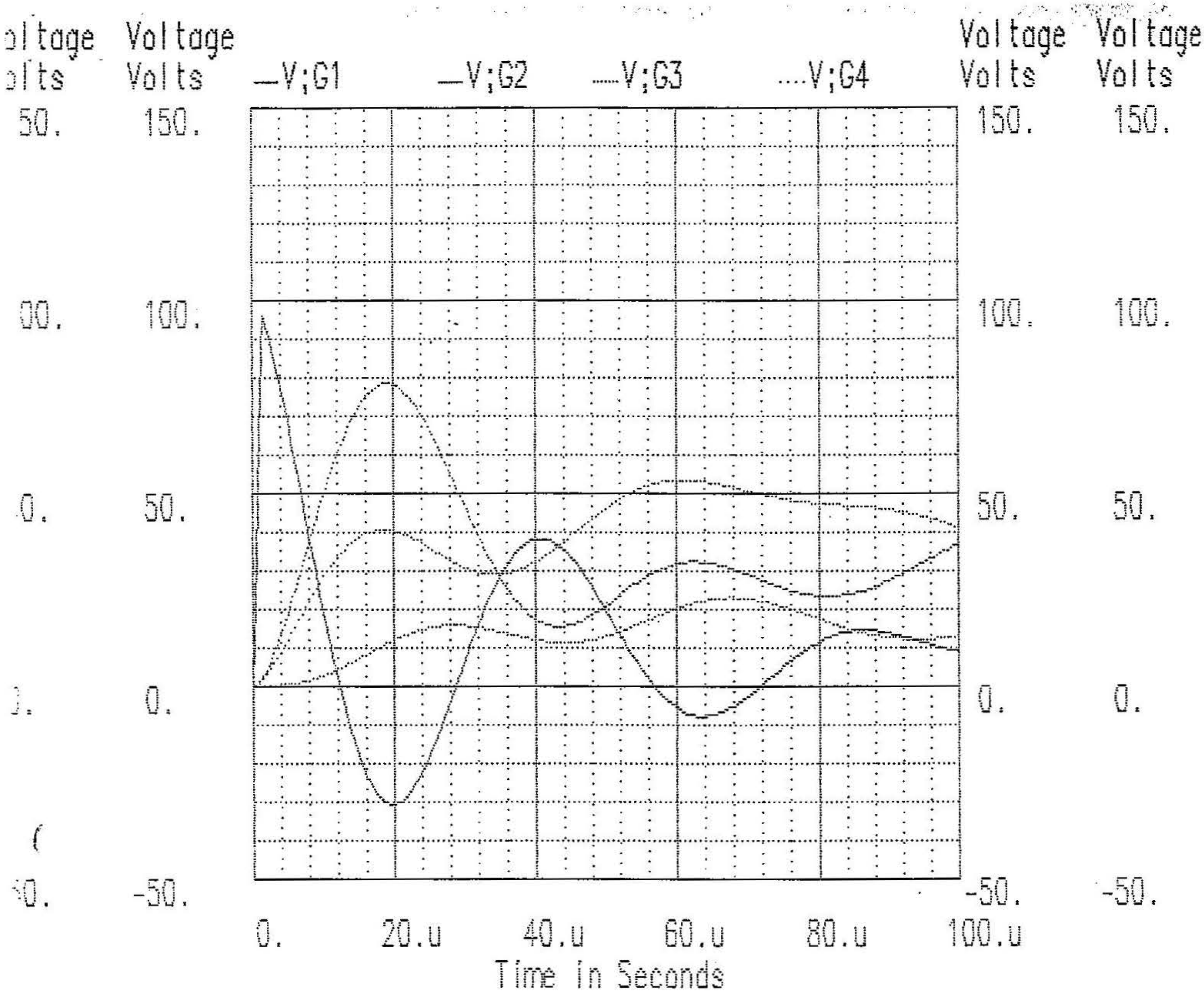


Figure 5

c50m2p.ckt

Coil-to-coil and coil-to-ground coupling C's and related R's are the same as in c50m1p.ckt.

Otherwise, same as c50m2b.ckt (M=0).

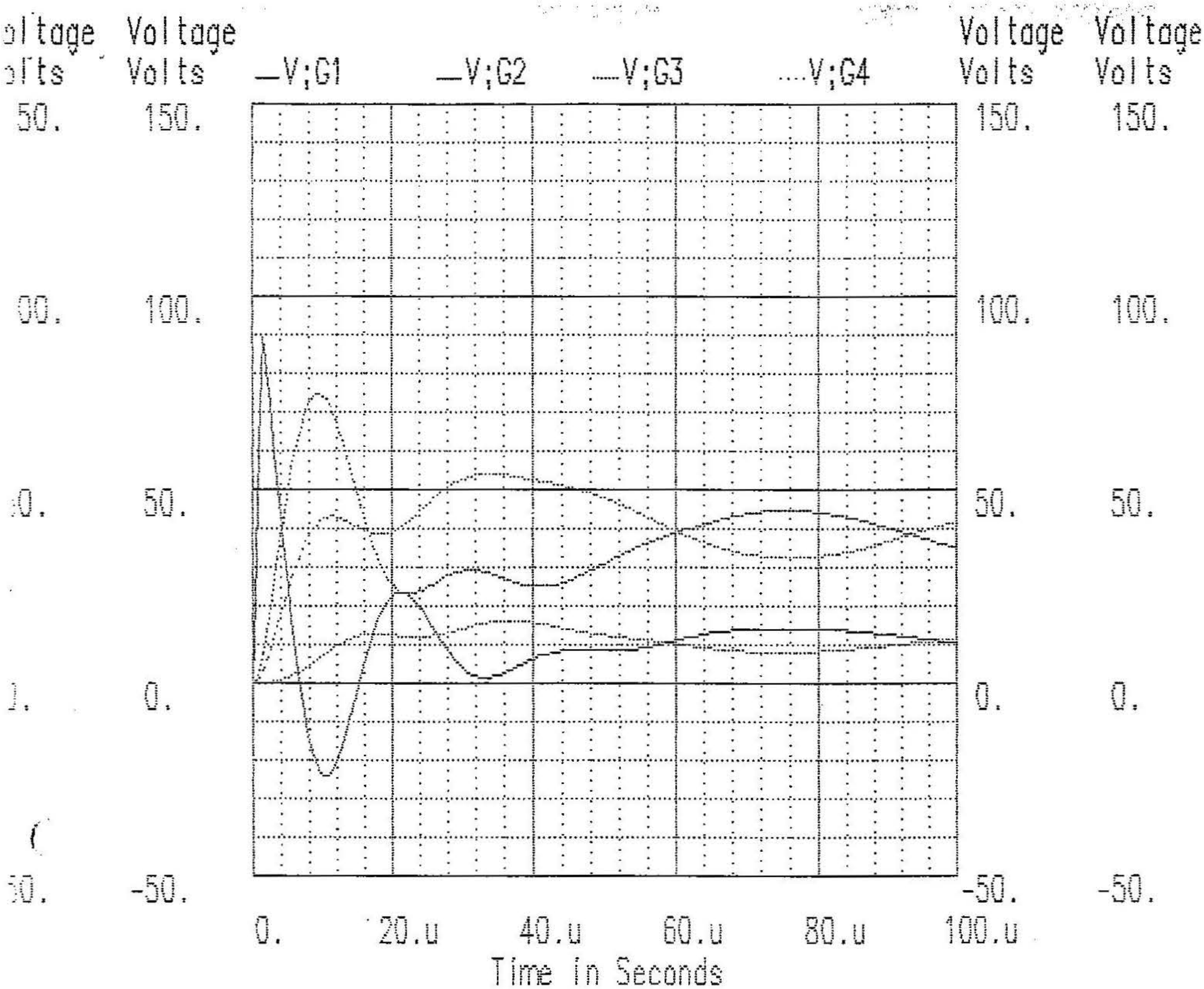


Figure 6

c5Øm1b.ckt

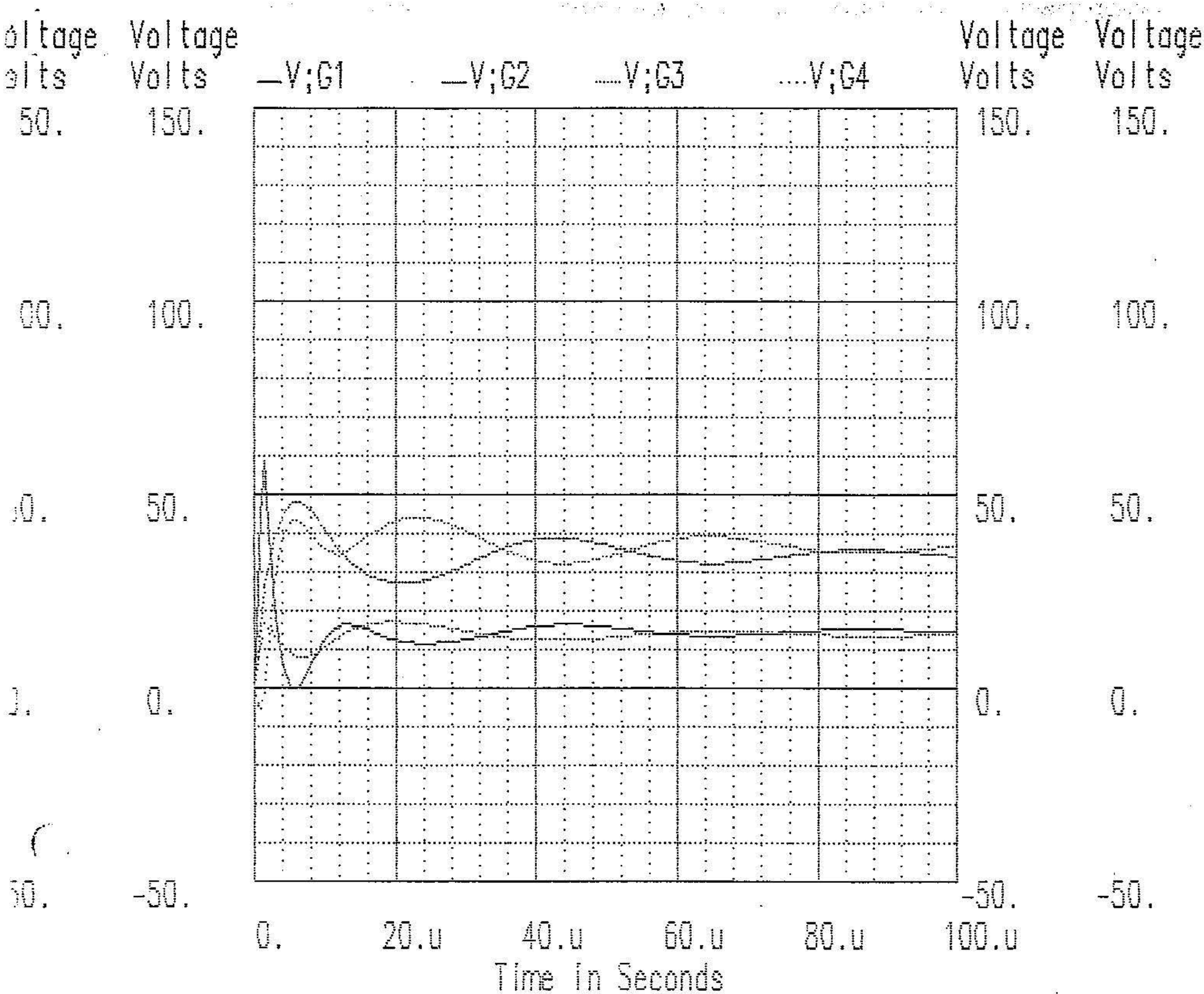


Figure 7

c50m1p.ckt

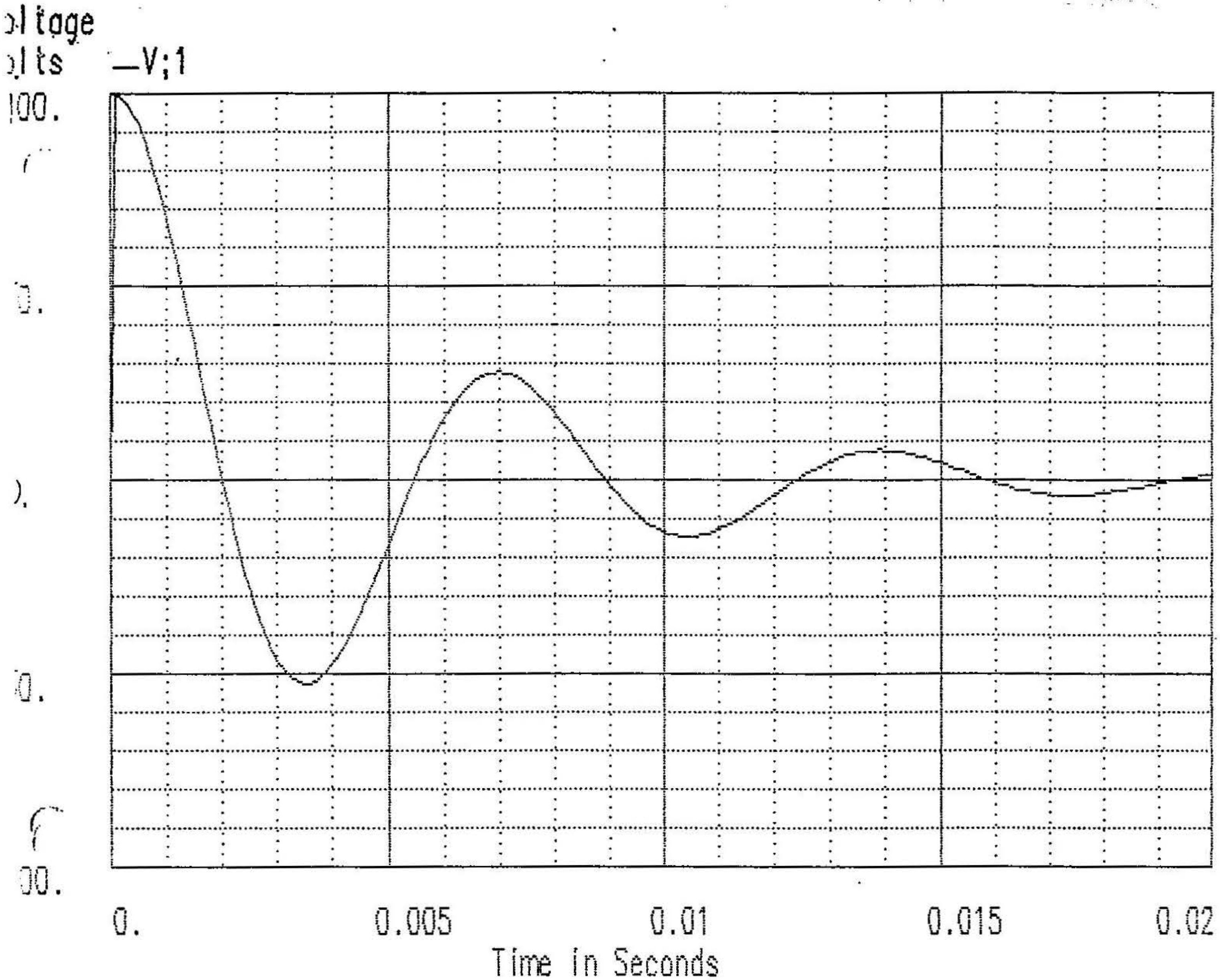


Figure 8

c5Ømlp

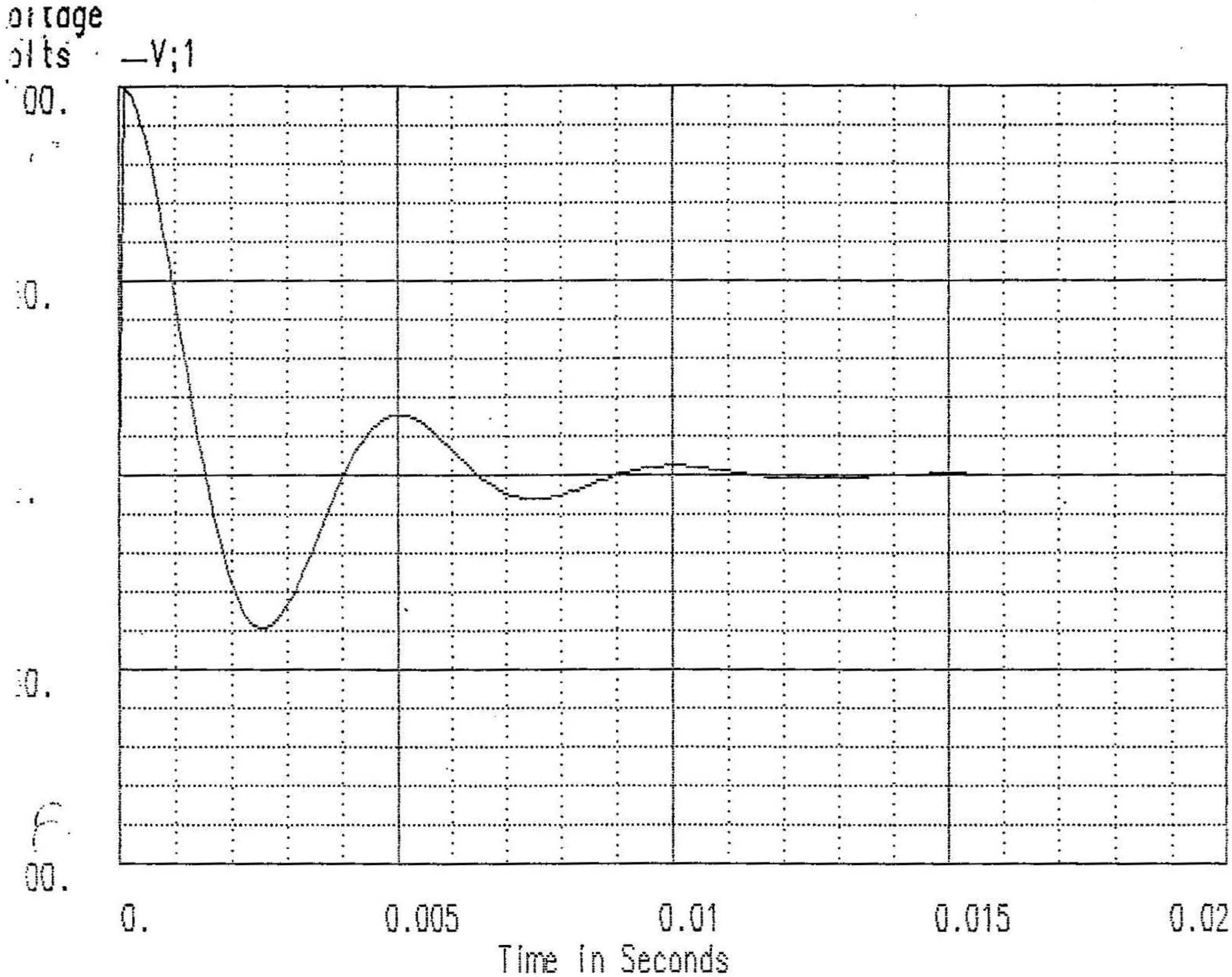


Figure 9

c50m1b