OPEN-LOOP OUTPUT IMPEDANCE AND INTERFACE INTERMODULATION DISTORTION IN AUDIO POWER AMPLIFIERS

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ABSTRACT

It has recently been postulated that power amplifiers with high open-loop output impedance and large feedback factor are more likely to produce intermodulation distortion at the loudspeaker interface (IIM). With the aid of computer simulations, this possibility is examined in the context of contemporary amplifier circuits. It is found that there is no fundamental reason for increased IIM in such amplifiers given proper design.

INTRODUCTION

A new form of distortion in audio power amplifiers, termed "interface intermodulation distortion" (IIM), has recently been described.[1] Based on the analysis presented, it was concluded that this distortion, occurring at the amplifier-loudspeaker interface, is more likely to occur in amplifiers having high open-loop output impedance and large feedback factors.

Many contemporary power amplifiers approach or fall into this category, and these results are therefore cause for concern and demand further investigation.

The production of IIM is re-examined in this paper, but with a viewpoint different from that of the earlier paper. Computer simulations of two realistic contemporary power amplifier designs are employed to generate an A-B comparison. The two designs are identical in every respect except that one is characterized by low open-loop output impedance and low feedback factor while the other is characterized by high open-loop output impedance and high feedback factor. The only circuit difference between the two is the inclusion or deletion of a load resistance in the collector circuit of the pre-driver common-emitter stage. This technique guarantees that only the characteristics under discussion are influential in the comparison. Both linear and transient simulations are utilized.

A strong advantage of the simulation technique is the ability to perform "experiments" with great accuracy and to observe activity in any portion of the circuit with relative ease. The technique also eliminates the need to make many simplifying assumptions which may lead to erroneous conclusions.

WHAT IS IIM?

Audible, low-frequency differences between amplifiers under actual speaker-loading conditions, when the amplifiers in question produce very good performance by conventional measures in the lab into a resistive load, may be at least partly a result of what has been termed interface intermodulation distortion (IIM).

Anyone who has ever seen the impedance versus frequency characteristic of a loudspeaker knows that the speaker presents a fairly complex load to the amplifier, often with several significant resonances. The impedance can sometimes rise to over ten times its rated value and fall to less than 80 percent of its rated value. However, simple network theory tells us that if the amplifier has a high damping factor (DF), frequency response errors created by this complex loading of the amplifier should be minimal. For example, the resulting frequency response differences due to such loading between two amplifiers, one with a DF of 50 and the other with a DF of 100, should be on the order of 0.1 dB or less.

The electromechanical system of the speaker (particularly the woofer) also represents an energy storage and generation capability, since any movement of the cone will cause an e.m.f. to be generated by the voice coil-magnet system. This movement could be due either to cone momentum developed by earlier excitation or to sound or vibration in the acoustical environment of the speaker. The capability thus exists for the speaker to inject a signal back into the output of the amplifier. If this signal makes its way back to the amplifier input via the feedback network (i.e., as an error-correction signal) and subsequently travels through the nonlinearities in the forward path of the amplifier along with legitimate input signals, intermodulation distortion may result. This distortion mechanism has been termed interface intermodulation distortion (IIM), and it has been postulated that this may partly account for audible differences among amplifiers not accounted for by conventional measurements.[1] IIM has been more formally defined in Reference 1 as follows on next page.

"Interface Intermodulation is a form of distortion in a two-port, caused by nonlinear interaction between the output signal of the two-port, and a signal externally injected to the output."

THE ISSUES

In an earlier paper on the subject, it was stated that IIM is produced in amplifiers using high values of negative feedback, and having moderate or high open-loop output impedance in comparison with the loudspeaker impedance.[1] In essence, the concern is that a high damping factor produced synthetically by a high feedback factor does not provide intrinsic damping at the amplifier output, and that the signal injected by the loudspeaker is therefore forced to circulate in the feedback loop to provide the necessary correction signal, thus encountering opportunities for intermodulation with the input signal. It has further been implied that a low open-loop output impedance provides a true physical impedance which can damp most of the injected signal right at the output, with less resort to circulating correction signals.

Although this intuition expressed in Reference 1 seems plausible at first glance, it needs to be more carefully examined, as it has fairly serious implications for selection of amplifier topology and characteristics. As in the case of transient intermodulation distortion (TIM), it represents an indictment of the use of large values of negative feedback. That has been shown not to be justified with TIM;[2,3] we will here attempt to see if it is the case with IIM.

In treating the problem, only the energy storage effect of the loudspeaker will be considered, as it has already been shown to be more significant than the generator effect.[1] The simple RLC electrical model of the loudspeaker shown in Fig. 1 will be used. In this model, R represents the d.c. voice coil resistance, C accounts for the mass of the cone, and L accounts for the suspension compliance. The model assumes a closed-box speaker system and ignores the effects of crossovers, other drivers, etc. In all cases we will make the conventional assumption that the minimum speaker impedance at low frequencies is equal to 80 percent of rated impedance.

Most of the investigation will simply be concerned with the effect of an arbitrary current injected into the output terminal of the amplifier without regard to its source.

The essence of the problem is to determine what factors influence how much of the injected signal ends up travelling in the forward path along with an input signal.

MODELLING THE PROBLEM

The simplified feedback amplifier may be modelled by means of either a Thévenin representation as shown in Fig. 2, or a Norton representation as shown in Fig. 3. Each representation is valid, but the insight provided can be slightly different.

In Fig. 2, the open-loop amplifier is represented by a block of voltage gain A, in series with the open-loop output impedance, Z_{ol}. Negative feedback is provided by feedback network B (providing loss) and the summer. We assume that B is a high-impedance element and neglect current flow into it.

It is very important when using this model to recognize that voltage V4 may not exist in reality and thus has limited significance. Failure to recognize this may have contributed to earlier erroneous conclusions.[1]

The no-load feedback factor for the circuit of Fig. 2 is simply $A \cdot B$, and the closed-loop output impedance, Z_{cl}, can be found by applying a voltage to the output and calculating the resultant current flow, with the result:

$$Z_{cl} = Z_{ol} \parallel \frac{Z_{ol}}{A \cdot B} \approx \frac{Z_{ol}}{A \cdot B} \qquad (1)$$

We see that the closed-loop output impedance is less than the open-loop output impedance by the factor $1+A \cdot B$, as expected. For most normal situations, where Z_{cl} is significantly less than Z_{ol} (i.e., $A \cdot B >> 1$), the second term in (1) is dominant, and the approximation shown is justified. It should be recognized that in reality Z_{ol}, Z_{cl}, A, and sometimes even B will be functions of frequency.

In the Norton model of Fig. 3, the open-loop amplifier is represented as a transconductance, gm, in parallel with Z_{ol}. In this case, the no-load feedback factor is $g_m \cdot Z_{ol} \cdot B$ and the closed-loop output impedance is easily found to be as follows on next page.

$$Z_{cl} = Z_{ol} \parallel \frac{1}{g_m \cdot B} \approx \frac{1}{g_m \cdot B} \qquad (2)$$

As before, when Z_{cl} is significantly less than Z_{ol}, the second term in (2) is dominant, and we see that feedback factor and Z_{ol} do not appear in this term. What has actually happened in the model is that as Z_{ol} is increased, the feedback factor is also increased in proportion, leaving the closed-loop output impedance unchanged if the insignificant first term of (2) is ignored.

The insight provided by the model of Fig. 3 seems more relevant to power amplifier design because power amplifiers with high open-loop output impedances tend to have commensurately higher no-load feedback factors.

To develop further insight, a slightly more detailed Norton-like, low-frequency model of a power amplifier is shown in Fig. 4. In this model, the open-loop amplifier consists of three active stages: an input voltage amplifier stage, A_1; an intermediate transconductance stage, g_{m1}; an output current amplifier stage, h_{fe}. These correspond loosely to the input differential amplifier, the common emitter pre-driver, and the common-collector double- or triple-Darlington output stage, respectively, of a typical power amplifier. A different model might be more appropriate for certain high-frequency investigations, such as for transient intermodulation distortion (TIM).

This model serves to illustrate separately the two major components of the open-loop output impedance. The first is the effective impedance at the pre-driver collector node, Z_1, divided by the current gain of the output stage. Z_1 may be a very high impedance at low frequencies in designs using various forms of active loading (e.g. current source), but in most cases decreases considerably at higher frequencies (this is especially true in designs using Miller-effect feedback compensation). The second component of Z_{ol} is represented by R_e, the net sum of the output transistor dynamic emitter resistance and the physical emitter resistors. This second component is fairly flat with frequency and is generally on the order of 0.1 - 0.3 ohms. Mathematically,

$$Z_{ol} \approx (Z_1/h_{fe}) + R_e \qquad (3)$$

In most cases the first term dominates in Z_{ol}. As before, notice that doubling Z_1 will approximately double both the open-loop output impedance and the feedback factor, leaving closed-loop output impedance unchanged. Increasing h_{fe} will decrease open-loop output impedance without substantially changing the no-load feedback factor, thus decreasing closed-loop output impedance for a given feedback factor. Extremely high damping factors are easily achieved in this way by using, for example, a triple-Darlington output stage with an h_{fe} on the order of 100,000.

FEEDBACK, OUTPUT IMPEDANCE AND IIM

Couched in the proper terms, the IIM problem becomes extremely simple: given a current injected at the output of the amplifier, how much voltage makes its way back to the input via the feedback network? Armed with a proper understanding of how feedback and open-loop output impedance influence closed-loop output impedance, the question is easily answered. By definition, the closed-loop output impedance determines how much voltage is developed at the output terminal in response to the injected current. The voltage reaching the input and "circulating" in the feedback loop is simply that voltage times the factor B (usually 0.05, corresponding to a closed-loop gain of 20). Expressed mathematically,

$$V_2 = B \cdot Z_{cl} \cdot I_i \tag{4}$$

$$\approx I_i \, Z_{ol}/A \quad \text{(using Eq. 1)} \tag{5}$$

$$\approx I_i/g_m \quad \text{(using Eq. 2)} \tag{6}$$

where I_i is the injected current and V_2 is the resultant voltage fed back.

We can see clearly from (5) that it is incorrect to state that amplifiers having high feedback factors and high open-loop output impedance are more prone to IIM. Rather, it is their ratio which is important. For a given closed-loop gain, it is simply the closed-loop output impedance which is important. Equation (6) even more graphically illustrates the irrelevance of feedback or open-loop output impedance alone. We see also that the concept of so-called intrinsic damping at the output by a physical open-loop output impedance is of little value.

The problem can also be viewed from a slightly different perspective. For reasonable values of damping factor the voltage change induced at the output by the injected current is quite small. The primary effect, therefore, is that the amplifier must supply the amount of the injected current as well as the legitimate signal current. The input-referred error voltage required to supply these currents is therefore inversely proportional to the net transconductance (g_m, not just g_{m1}) of the open-loop amplifier, regardless of the value of Z_1 in Fig. 4. A low value of Z_1 (low feedback, low open-loop output impedance design) will, however, add an additional input-referred error voltage which depends on the output signal voltage swing. Although this additional signal-dependent error voltage may reduce the referred error voltage caused by injected current as a percentage of the total error voltage (i.e., mask it), the magnitude of the latter will remain unchanged and so the probability of IIM.

The prescription for low IIM is not simply a low open-loop output impedance, but rather an extremely high net transconductance in the open-loop amplifier. This is easily achieved in practice.

A CONTEMPORARY POWER AMPLIFIER

In order to lend perspective to the previous sections and to confirm some of the conclusions, a simple contemporary power amplifier design will be discussed and subjected to analysis by computer simulation techniques. The experimental vehicle is shown in Fig. 5. Although it is somewhat simpler than many current amplifier designs, it is representative of contemporary topology. No claim is being made that this is a superior design.

The circuit incorporates the classic topology of the differential input stage, common-emitter predriver stage (with current source load), and complementary double Darlington output stage. Emitter degeneration provided by R3 and R4 allows a respectable slew rate of about 25 V/μs for good TIM performance. Capacitor C3 provides Miller-effect feedback compensation for a stable closed loop bandwidth of about 1 MHz. Transistors Q3-Q5 form a Darlington/cascode predriver stage which provides very good linearity and extremely high output impedance. Notice that this amplifier is well represented by the model of Figure 4.

In order to test the findings of the previous sections, we will examine two amplifier designs identical in every respect except that one is characterized by low open-loop output impedance and low feedback factor while the other is characterized by high open-loop output impedance and high feedback factor. We expect to find that the closed-loop output impedances of these two designs will be essentially identical and further expect the IIM characteristics to be the same. The differing characteristics of the two amplifiers are determined by pre-driver collector load resistors R11 and R12; the value of these resistors is the only circuit difference. This technique guarantees that only the characteristics under discussion are influential in the comparison. A very high value of R11-12 (10M) achieves the high-feedback, high-Z_{ol} Case A, while a low value (10K) achieves the low-feedback, low-Z_{ol} Case B. The high output impedance of the cascode pre-driver stage is important in achieving adequately high Case-A Z_{ol} for the purposes of the comparison.

The ac analysis results shown in Figures 6-8 will help us get acquainted with the amplifier and confirm some earlier reasoning. Figure 6 shows no-load open- and closed-loop gain for both cases. Case A exhibits a low-frequency feedback factor of about 61 dB and an open-loop bandwidth of about 800 Hz. Corresponding values for Case B are 28 dB and 30 kHz respectively. Closed-loop gain and bandwidth are indistinguishable for the two cases, as expected.

Figure 7 illustrates open- and closed-loop output impedance for both cases. Case A has a low-frequency Z_{ol} of about 72 ohms while the value for Case B is only 1.8 ohms. These values of Z_{ol} are similar to those found in the investigations of Reference 1. Notice that Z_{ol} for both cases is similar at higher frequencies where the pre-driver output impedance is controlled by the shunt feedback provided by the compensating capacitor C3. As expected from earlier discussions, the closed-loop output impedance for both cases is almost identical. Notice also, that for both cases Z_{ol} and Z_{cl} differ by a ratio approximately equal to the feedback factor, as expected. Finally, earlier generalizations elsewhere that Z_{cl} becomes inductive at the open-loop cutoff frequency and that Z_{cl} is more inductive for designs with small open-loop bandwidth are seen to be incorrect.[4]

For completeness, the open- and closed-loop gain is shown in Fig. 8 for both cases with an 8-ohm load. The low-frequency feedback factor in Case A is reduced significantly to about 41 dB due to the effect of loading on the fairly high open-loop output impedance. A reduction of less than 2 dB occurs for Case B. Performance is essentially unchanged at high frequencies with the exception of a slight increase in closed-loop bandwidth due to some reduction in phase margin.

AMPLIFIER NONLINEARITIES

Because IIM is primarily a low-frequency phenomena, low-frequency amplifier distortion mechanisms are at work. Although several of these mechanisms are common to both IIM and ordinary IM distortion production, one important distinction is worth noting. While IM distortion occurs when the amplifier is delivering both the voltage and current associated with a multiplicity of input signals, IIM distortion occurs when the amplifier is delivering the current associated with the input and reflected signals, but only the voltage associated with the input signal. Nonlinearities associated with output voltage swing are thus not as strongly exercized in the IIM situation, and this explains why IIM will generally be less than IM under equivalent testing conditions.

Power amplifiers generally have many sources of open-loop nonlinearity which together form a fairly complex nonlinear system, however, the level of the individual distortions is usually small enough so that superposition can be applied without serious error. This allows us to consider the contribution of each source individually. This approach is further justified by the fact that the total nonlinearity is often dominated by only one or two sources under any given set of operating conditions.

The open-loop distortion contributed by a given nonlinearity depends primarily on the severity of the nonlinearity and the level of excitation of the nonlinearity. For example, a substantial nonlinearity in an input stage where signal swings are very small may contribute negligible distortion compared to a less serious nonlinearity later in the amplifier where operating levels are much higher. The effect of various design decisions, such as topology and amount of open-loop gain, on the various operating levels is thus very important in determining distortion behavior.

Referring to the amplifier shown in Fig. 5, the differential input stage, the common-emitter predriver stage, and the common-collector output stage are all potential sources of low-frequency nonlinearity. The input stage is somewhat linearized by the emitter degeneration resistors and the differential signal levels here are fairly small at low frequencies, particularly in Case A where the subsequent voltage gain is quite high. Any distortion due to common-mode nonlinearities is not subject to this line of reasoning, however.

Distortion from the pre-driver stage is generally due to the exponential base-emitter characteristic and nonlinear Early effect. The former depends primarily on collector signal current level, while the latter depends on collector signal voltage. Early effect here can also contribute to open-loop output impedance nonlinearity. The cascode connection in Fig. 5 minimizes Early effect.

The output stage contributes low-frequency distortion due to voltage- and current-dependent beta variations and variations of transconductance (i.e., Re of Fig. 4) in the crossover region. The latter can also be viewed as a nonlinearity of open-loop output impedance.

The effect of negative feedback on distortion is most easily understood by working backwards from the output. We assume a perfect output and evaluate the input-referred distortion required to generate it, just as we do in calculating input-referred noise. Because the feedback signal under these conditions is perfect, the level of the input-referred distortion is the same for either open- or closed-loop conditions. Distortion percentage is reduced by feedback simply as a result of the larger pure component of the input signal required under closed-loop conditions. This technique is quite accurate when the referred distortion products are small compared to the total closed-loop input; i.e., when closed-loop distortion is small. It is important to remember that the gain involved in referring a distortion product back to the input may be a strong function of frequency.

Consider one of the major contributors to both IM and IIM: output stage beta variations with current. The output stage requires a nonlinear drive current from the predriver to produce a perfect output. This results in an input-referred distortion voltage when the transconductance of the input stage/predriver is considered. Notice that the value of the predriver load resistors will have virtually no effect on the level of this particular product because they have little effect on the transconductance.

IIM COMPUTER SIMULATIONS

In this section we will evaluate the IIM performance of the two amplifier designs by looking at various signals, both internal and external, as functions of time under various conditions. The plots generated by the transient analysis program utilized are essentially the same as what would be seen on an oscilloscope display if the experiments were carried out in the lab with a real amplifier.

Because the issue regarding the magnitudes of error signals circulating in the feedback loop due to currents injected at the output of the amplifier is central to the IIM discussion, the first "experiment" involved injecting a 56-V p-p, 50-Hz sinusoid into the output of the amplifiers through an 8-ohm resistor. The plots of the observed signals for this experiment are not shown because they were not very interesting - they were all quite sinusoidal, as expected. However, their magnitudes were worth noting. The peak-to-peak current swings at the collectors of Q1 and Q5 were about 20 μA and 2.0 mA, respectively, with Case B (R11=R12=10K) levels higher by about 10 percent. The slightly higher values in Case B are due to the additional error current which must be supplied to R11 and R12 so as to produce the necessary error voltage at the collector of Q5, which in both cases is about 1V p-p. The low-feedback, low Z_{ol} case thus actually has slightly higher circulating error signals, contrary to earlier beliefs.[1]

The results of a similar exercise are shown in Figures 9 and 10. Here a 56-V p-p, 2-kHz square wave has been applied to the amplifier output through 8 ohms. The square wave had 2.0 μS risetime and falltime. Starting from the output end of the amplifier, the plots illustrate the following signals:

(a) Injected current.

(b) Induced amplifier output voltage.

(c) Voltage at the junction of D5 and D6.

(d) Collector current of Q5.

(e) Collector current of Q1.

As before, the internal amplifier signals for Case A and Case B are almost indistinguishable, both in low-frequency characteristics (the step) and high-frequency characteristics (the overshoot). The overshoot is due to the normal inductive closed-loop output impedance (0.5 μH at 300 kHz) exhibited by these amplifiers at high frequencies (see Fig. 7). This test was also made with much lower frequency square waves, but no differences were observed other than the fact that some leading-edge overshoot detail was lost.

Having seen no significant differences between Case A and Case B for signals injected at the output, we will now take a look at the situation where the amplifier delivers a large voltage step into a simple RLC model of a loudspeaker like the one shown in Fig. 1. The parameters in the model have been chosen to represent a "typical" loudspeaker with a dc resistance of 6.4 ohms, a fundamental system resonance of 50 Hz, and a Q of about 0.5. The fundamental resonance Q for most speaker systems is in the neighborhood of 0.5 to 1.0, so this is the primary area of interest for purposes of analysis. The low end of this range was chosen here because it yields a larger initial "kickback" or undershoot.[1] This choice did not strongly influence our basic results, however.

Figures 11 and 12 show the signals of interest for Cases A and B, respectively:

(a) Amplifier output voltage.

(b) Load current.

(c) Voltage at the junction of D5 and D6.

(d) Collector current of Q5.

(e) Collector current of Q1.

The load current rises suddenly to that which would flow in the 6.4 ohm dc resistance alone, dips deeply to about one-fourth this value, and gradually rises back to the earlier resistive value. The deepest point in the valley represents the point of maximum cone velocity and thus maximum counter-e.m.f. acting to lessen current flow. Although the dip looks like a large "oscillation" we should keep in mind that, at least for this experiment, it represents decreased amplifier taxation.

The internal amplifier signal excursions for Case A (R11=R12=10M) are generally smaller than for Case B. (Note different scales in (d) and (e) plots.) This is primarily due to the fact that R11 and R12 consume a substantial amount of drive current in Case B.

Another experiment, utilizing a different type of pulse input, shows that under certain conditions the RLC load is not quite as innocent as it appears above. As noted, the lowest point in the valley of the load current waveform, occurring about 4.0 milliseconds after the step, represents maximum cone velocity and counter-e.m.f.; the corresponding cone momentum represents significant stored energy. In the previous case, this e.m.f. acted to reduce current flow. What if, however, the polarity of the driving signal is suddenly reversed at this point in time, so that the e.m.f. acts to increase current flow? The results of such an experiment are illustrated in Fig. 13, where the amplifier output voltage and load current waveforms are shown.

The driving waveform in Fig. 13 was deliberately chosen to maximize the expected peak load current. The signal swings between large negative and positive values, rather than simply starting from zero. It stays at one extreme for 16 milliseconds to allow load current to rise to at least ninety percent of its final value. A 4.0 millisecond pulse then follows, with the trailing edge of this pulse reversing the applied polarity just when the counter e.m.f. is at its maximum. The situation is then repeated for the opposite polarity sense so that the average value of the signal is zero.

While an amplifier delivering this waveform to an 8-ohm resistive load would normally see a peak load current of about 3.5A, we see from Fig. 13 that the RLC load develops a peak load current of 10A! While the probability and extent of this kind of occurrence in the real world with musical program may be questioned, the exercize does provide some food for thought. As before, this situation is handled similarly by the Case A and Case B amplifiers, so feedback factor and open-loop output impedance are not at issue here. The only lesson to be learned here is to be prepared to handle larger currents than are encountered with a simple resistive load.

EXPERIMENTAL RESULTS

As further verification of our findings, the power amplifier of Fig. 5 was constructed and tested for Case A and Case B conditions. The amplifier, which clipped at a level of 50 watts into an 8-ohm load, was first tested for SMPTE IM (60 Hz and 6 kHz, 4:1) at a level of 45 watts. Case A IM was 0.1 percent, while Case B IM was 0.3 percent. The higher Case B IM is directly attributable to increased exponential base-emitter distortion in the predriver, where substantially larger signal current swings are involved in satisfying the current requirements of the low-value Case B collector load resistors.

IIM was next measured in a manner equivalent to the procedure outlined in Reference 1. Equal-level 1000-Hz 60-Hz signals were applied to opposite ends of an 8-ohm load resistor by the amplifier under test and a second power amplifier, respectively. A spectrum analyzer was placed across the output of the amplifier under test and the rms sum of the distortion products was referred to the 1-kHz level. The operating level of each amplifier was 25 watts. IIM for Case A was 0.052 percent, while that for Case B was slightly higher at 0.063 percent. These results confirm our other findings.

CONCLUSION

We have examined the IIM mechanism and have looked at internal amplifier error signals induced by signals externally injected at the output of amplifiers with high and low values of open-loop output impedance (Z_{ol}). The use of detailed computer simulations of real amplifier circuits has minimized the need for simplifying assumptions which could lead to erroneous conclusions.

Based on this investigation, we can conclude that, contrary to earlier expressed concerns, high feedback factor and high open-loop output impedance do not increase the likelihood of IIM. Rather, what is important is the ratio of these quantities, or simply closed-loop output impedance. Because extremely low Z_{cl} is easily achieved in practice, IIM is probably not a significant problem in most modern amplifiers where adequate current drive capability exists.

In a somewhat philosophical sense, the concern that high feedback factor and high Z_{ol} causes IIM seems to arise out of the same kind of misunderstanding of the operation and application of negative feedback which prompted many to erroneously conclude that large feedback factor and narrow open-loop bandwidth caused TIM. While it is not a universal panacea, negative feedback does perform as advertised when correctly analyzed.

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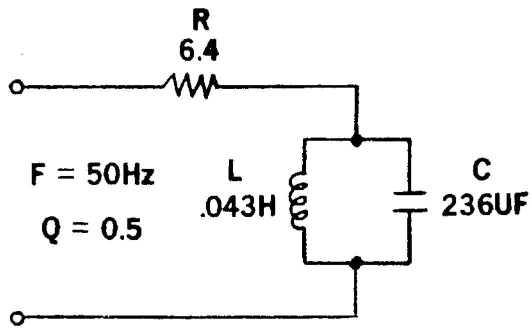

FIGURE 1: Simplified Loudspeaker Model

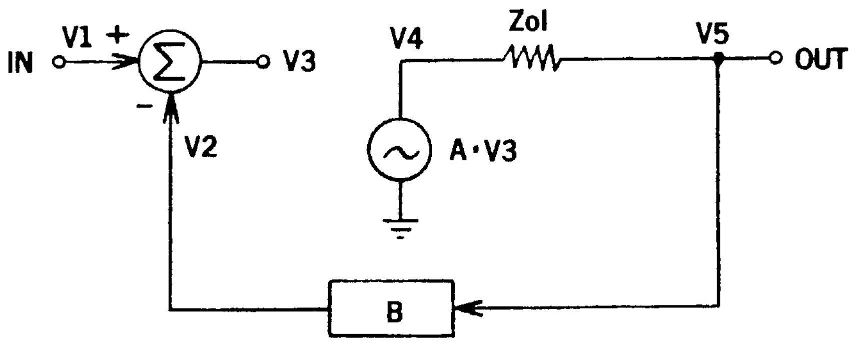

FIGURE 2: Thévenin Amplifier Model

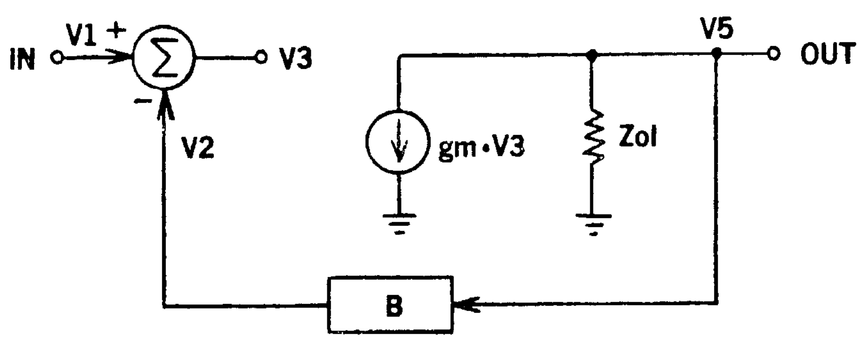

FIGURE 3: Norton Amplifier Model

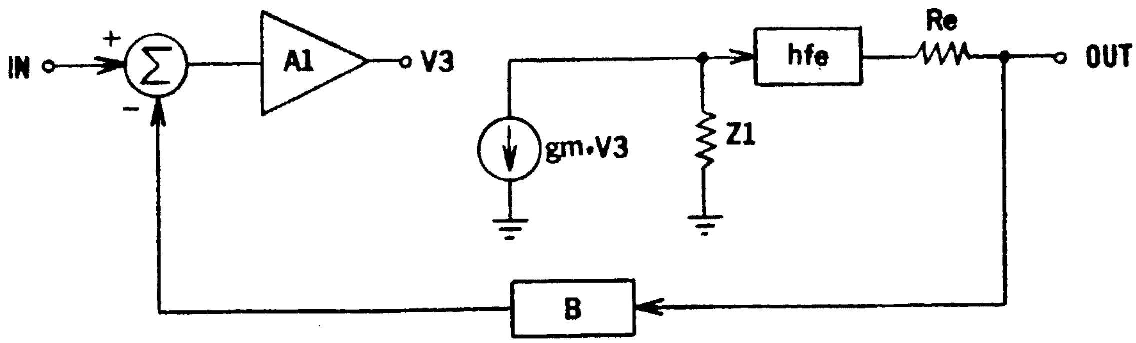

FIGURE 4: More Detailed Amplifier Model

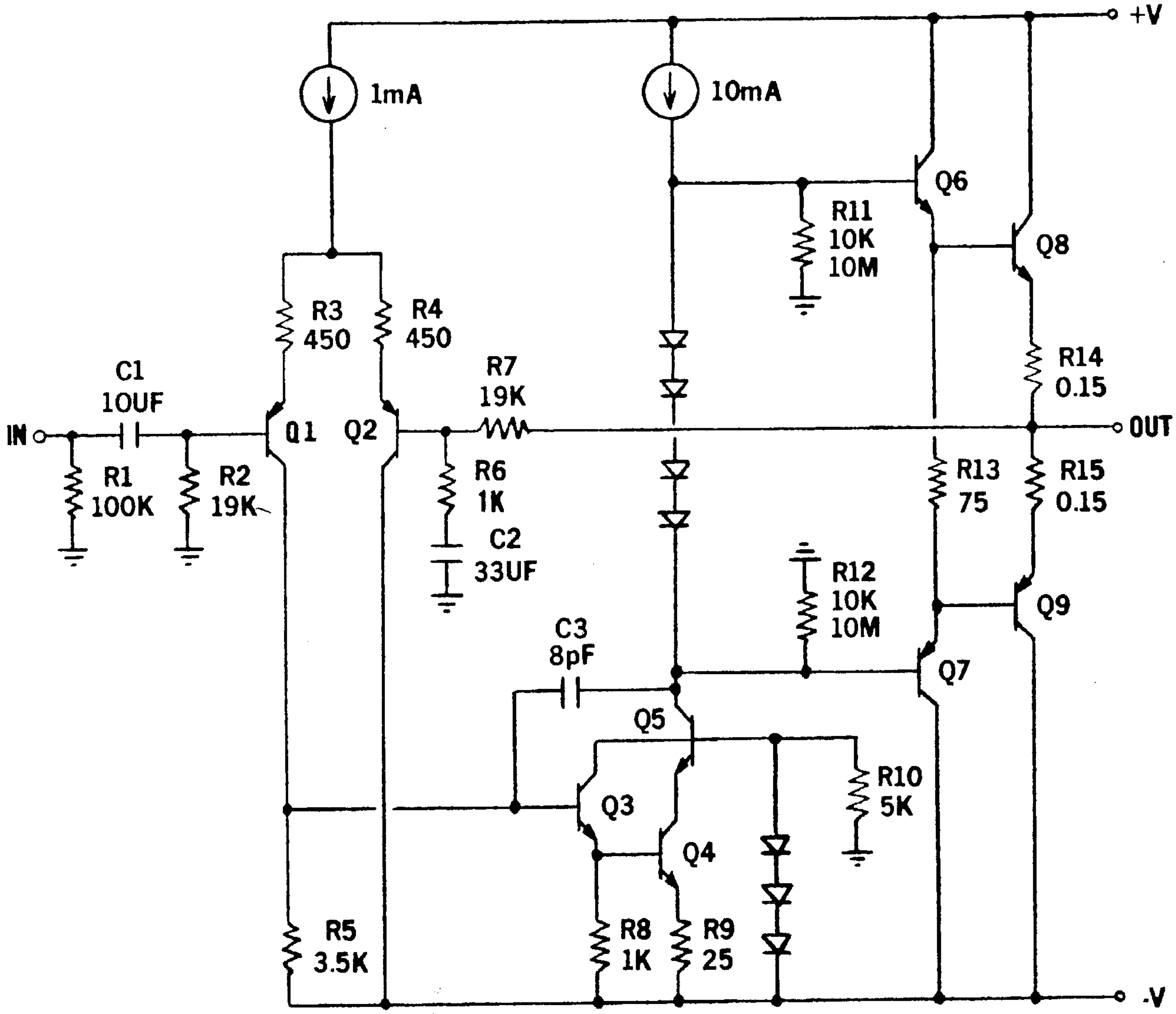

FIGURE 5: Power Amplifier to be Simulated.

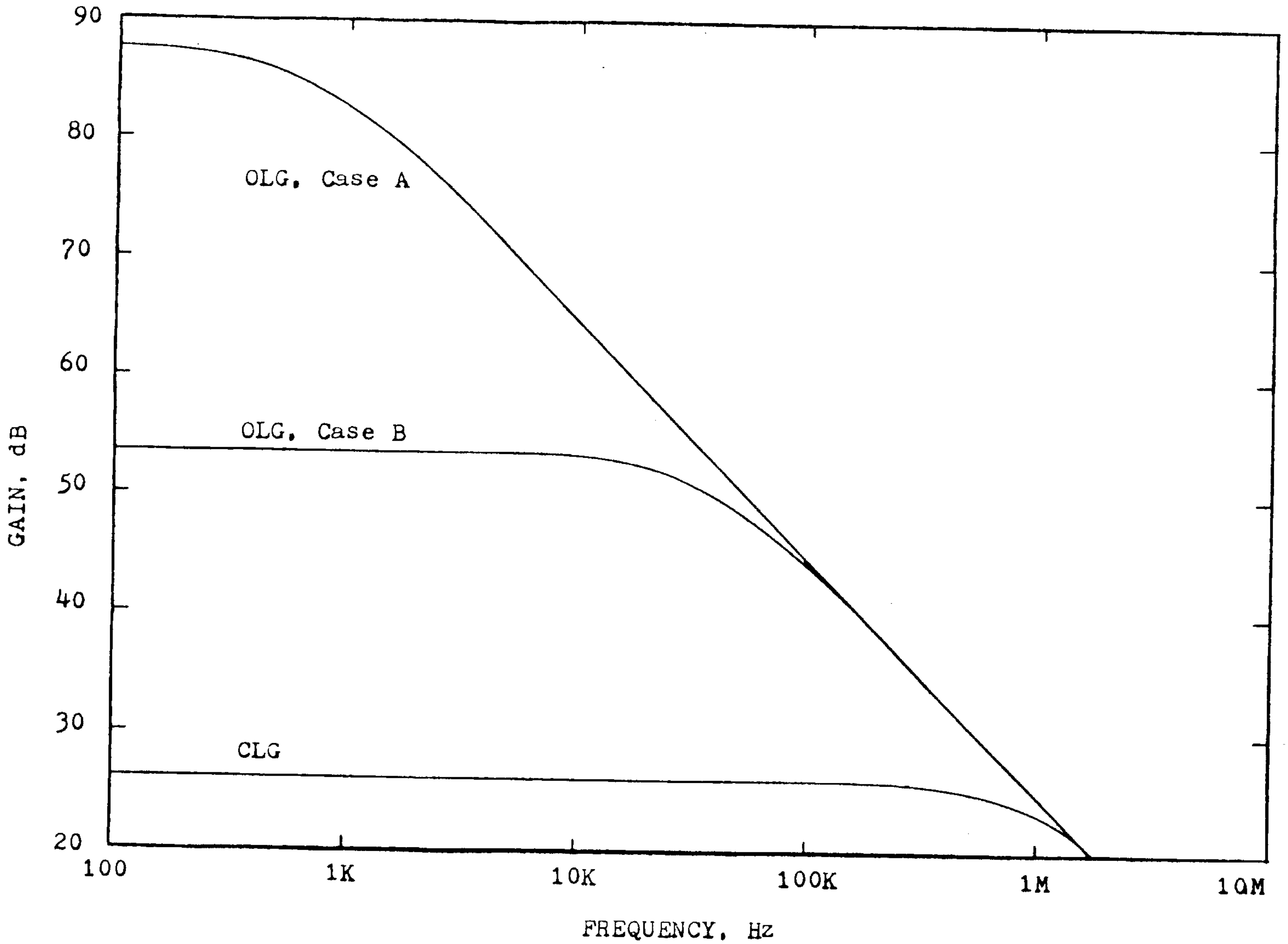

FIGURE 6: Amplifier open- and closed-loop gain (no load).

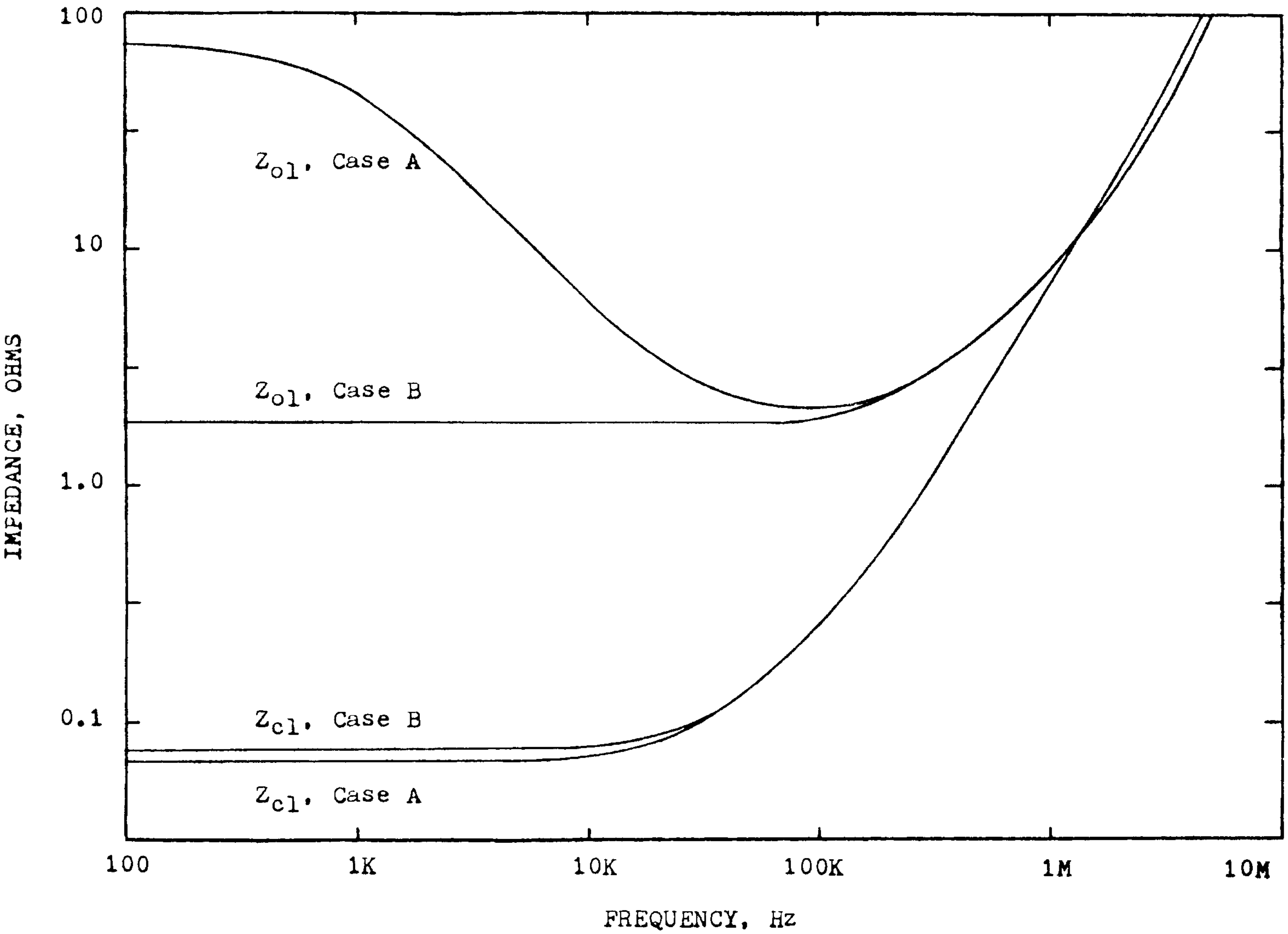

FIGURE 7: Amplifier open- and closed-loop output impedance.

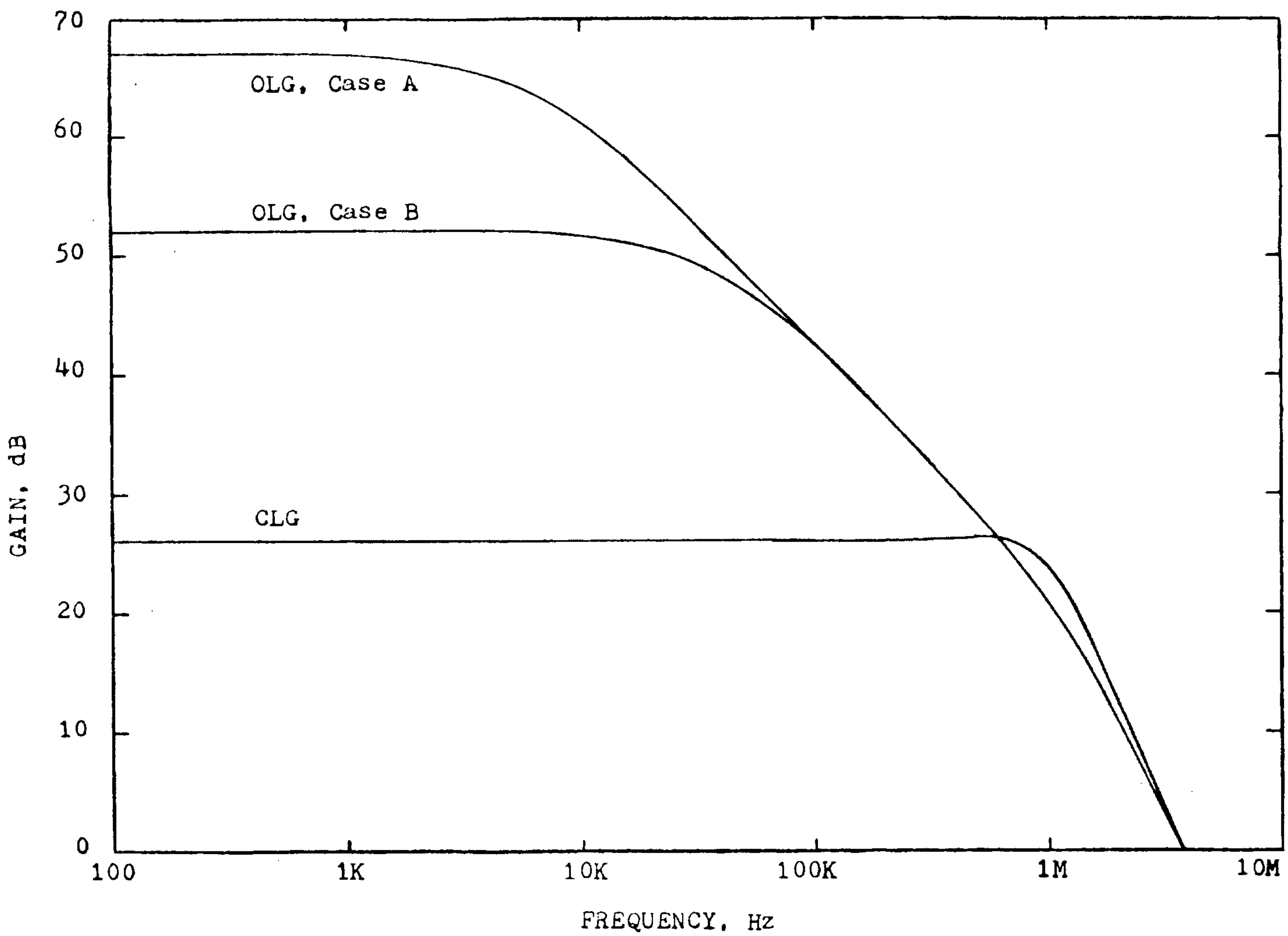

FIGURE 8: Amplifier open- and closed-loop gain with 8-ohm load.

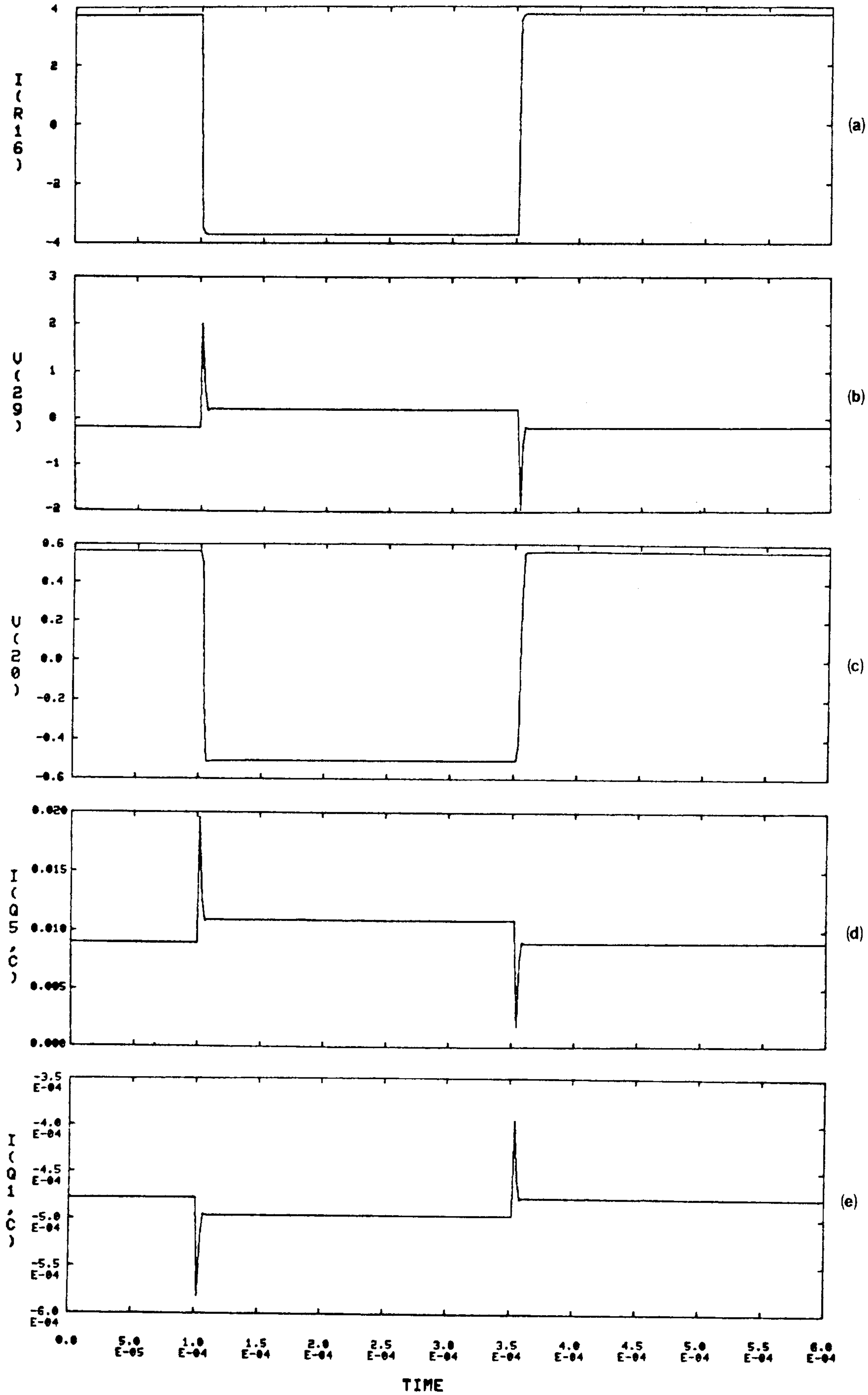

FIGURE 9: Square wave into amplifier output through 8 ohms, Case A (R11=R12=10M). a) injected current b) induced voltage at output c) voltage at D5-D6 d) Q5 collector current e) Q1 collector current.

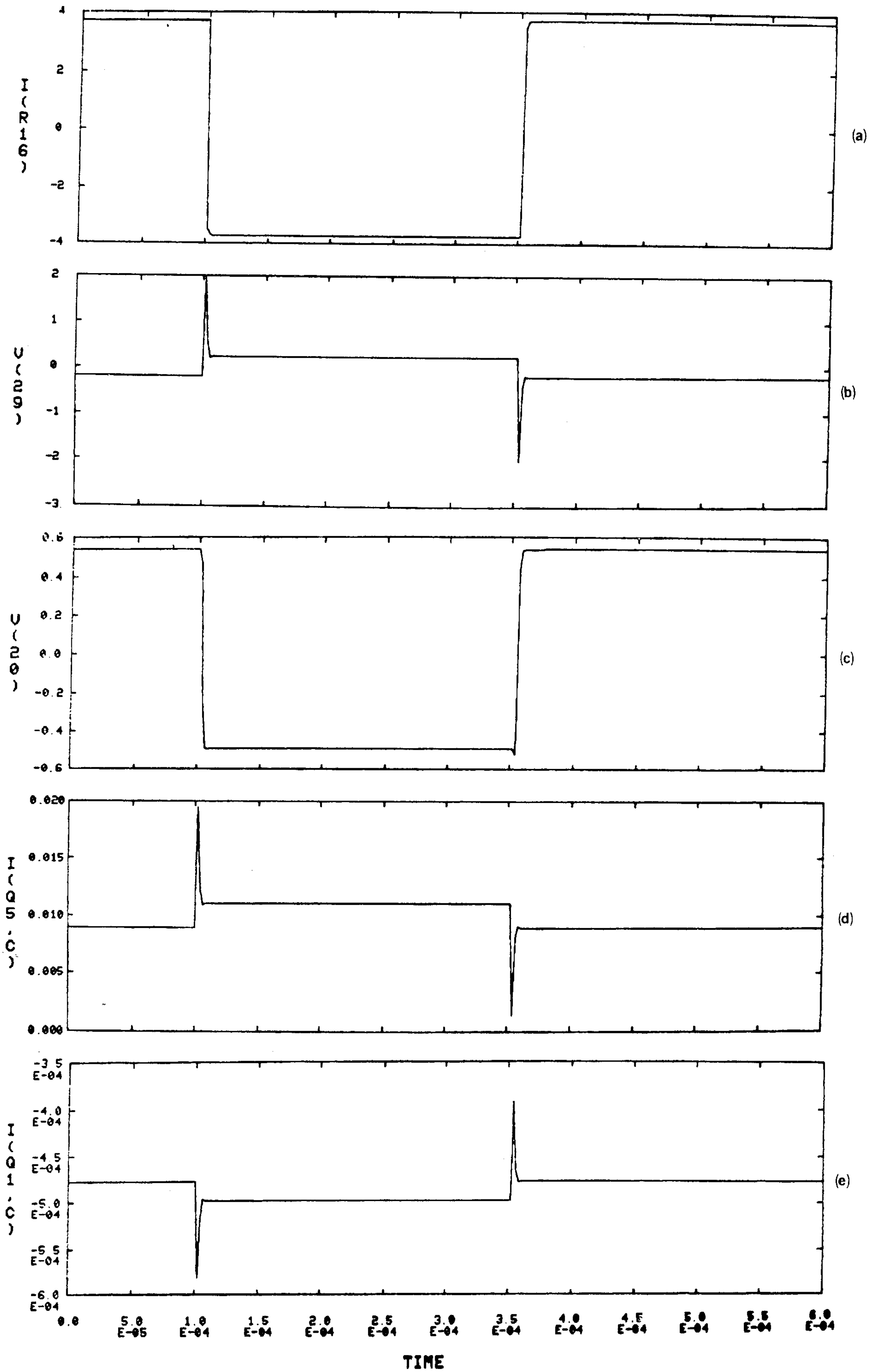

FIGURE 10: Square wave into amplifier output through 8 ohms, Case B (R11=R12=10K). a) injected current b) induced voltage at output c) voltage at D5-D6 d) Q5 collector current e) Q1 collector current.

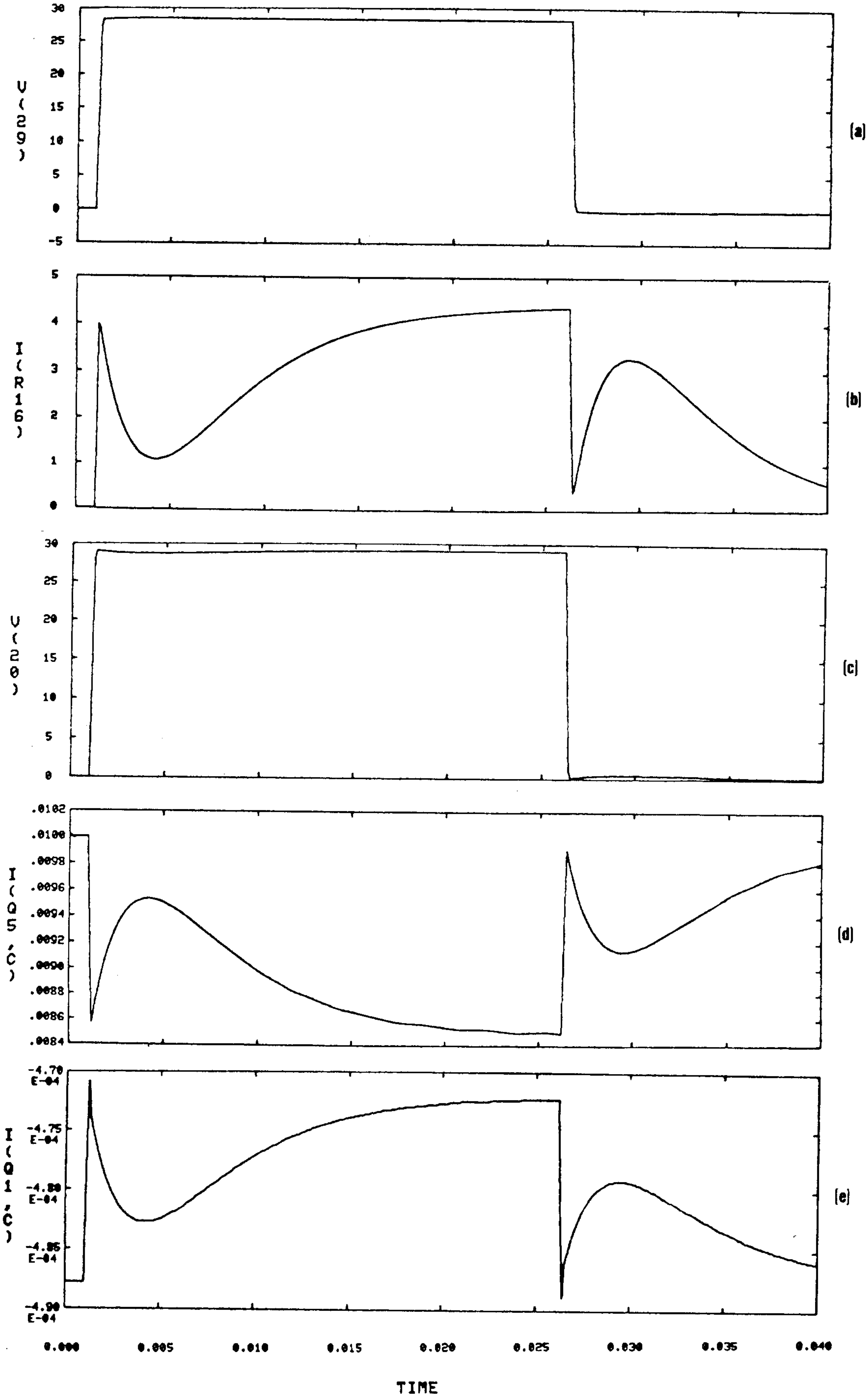

FIGURE 11: Voltage step into RLC load, Case A (R11=R12=10M).
a) amplifier output voltage b) load current c) voltage at D5-D6
d) Q5 collector current e) Q1 collector current.

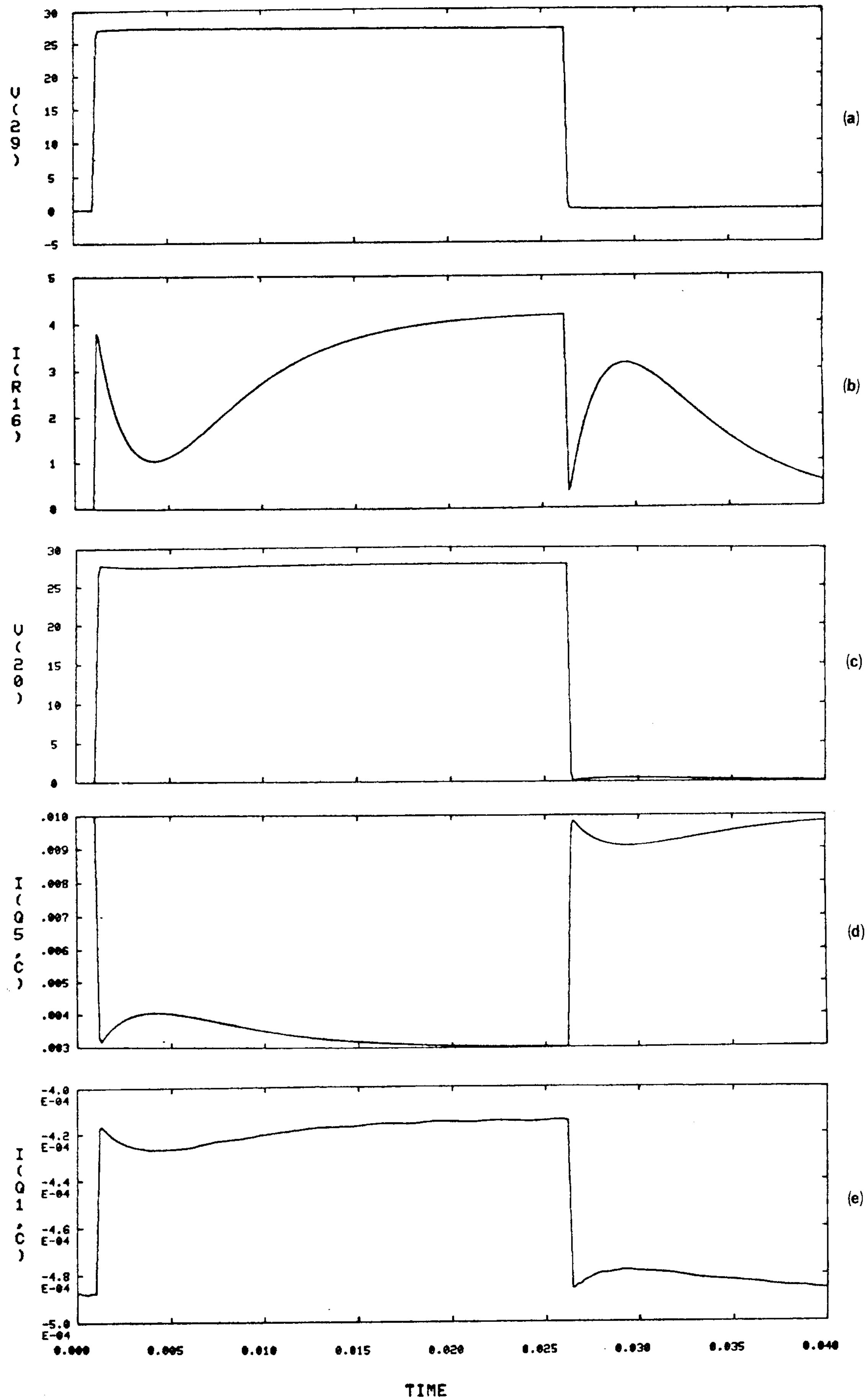

FIGURE 12: Voltage step into RLC load, Case B (R11=R12=10K).
a) amplifier output voltage b) load current c) voltage at D5-D6
d) Q5 collector current e) Q1 collector current.

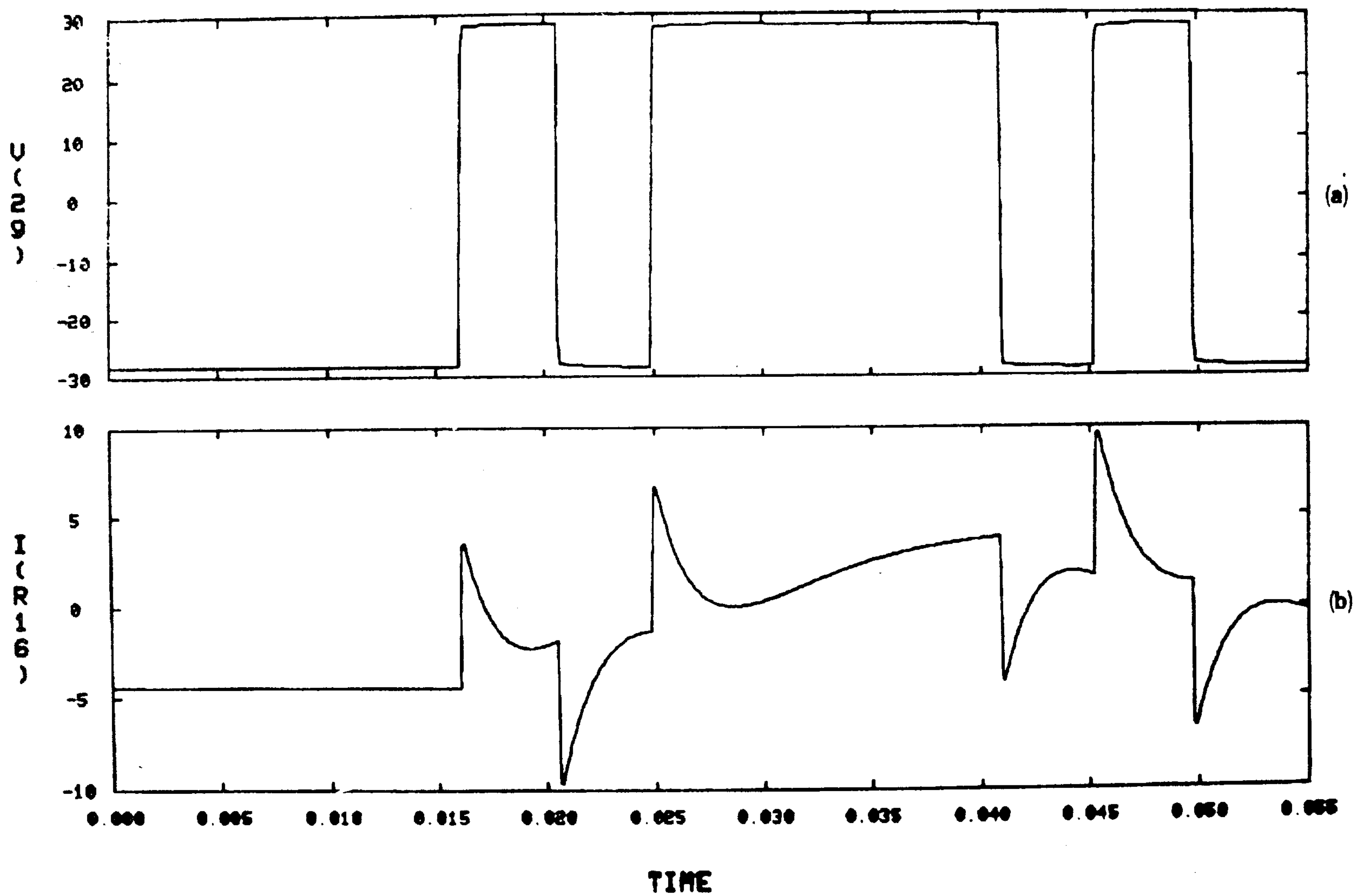

FIGURE 13: Special pulse voltage signal into RLC load illustrating unusually large currents which can flow under certain conditions. a) amplifier output voltage b) load current.