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AN ANALYSIS OF TRANSIENTS IN TUNNEL-DIODE CIRCUITS

by

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ABSTRACT

An analysis is performed for the transient response of a tunnel-diode modeled by a circuit of two capacitances, an inductor, and the dc i-v characteristic of the diode. The nonlinear differential equations of the transition are solved numerically, and waveforms are presented for a wide range of circuit parameters.

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The transient response for a ramp-function drive current of a tunnel-diode, modeled by a capacitance parallel with a voltage-varying resistor, was analyzed in a previous paper.[1] In this report the analysis is extended to the model of Fig. 1 incorporating an inductance and two capacitances. The dc i-v characteristic of the tunnel-diode is described by the function $i_D = I_p\left[e \cdot (v_D/V_p) \cdot \exp(-v_D/V_p) + 5 \times 10^{-10} \exp(3v_D/V_p)\right]$ shown in Fig. 2.

The differential equations of the transient were converted to difference equations and computed on the IBM 360/75 digital computer utilizing a program with the flow-chart of Fig. 3; the Fortran-H program is shown in Fig. 10. Waveforms of the normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with normalized drive current slope $A \equiv C_1 V_p k/I_p^2 = 0.01,\ 0.02,\ 0.05,\ 0.1$ are shown in Fig. 4 through Fig. 9 for $C_2/C_1 = 0.02,\ 0.05,\ 0.1,\ 0.2,\ 0.5,\ 1.0$ and for $L \equiv I_p^2 L_1/\left(V_p^2 C_1\right) = 0.1,\ 0.2,\ 0.5,\ 1.0,\ 2.0,\ 5.0$.

As an example, if a fast tunnel-diode with an $I_p = 10$ mA, $V_p = 100$ mV, $C_2 = 0.5$ pF, and $L_1 = 0.5$ nH is used in a circuit with $C_1 = 10$ pF (mostly external to the diode) and with $k = 5$ mA/nsec, then $C_2/C_1 = 0.05$, $A \equiv C_1 V_p k/I_p^2 = 0.05$, and $L \equiv I_p^2 L_1/\left(V_p^2 C_1\right) = 0.5$, and the resulting transient is that of Fig. 5(c) with $A = 0.05$ and a time scale of $t/T = 100$ psec. It is seen that there is a ringing on the voltage rise, impeding subsequent timing operations. If, however, C_1 is reduced to 2.5 pF, then $C_2/C_1 = 0.2$, $A = 0.0125$, and $L = 2$, and the transient of Fig. 7(e) with $A = 0.0125$ and a time scale of $t/T = 25$ psec results. This has a smooth initial rise, and also a subsequent ringing which is usually preferable to the ringing on the rise. If capacitance C_1 cannot be reduced, ringing on the rise can be eliminated by increasing C_2, i.e., by the use of a "slower" tunnel-diode.

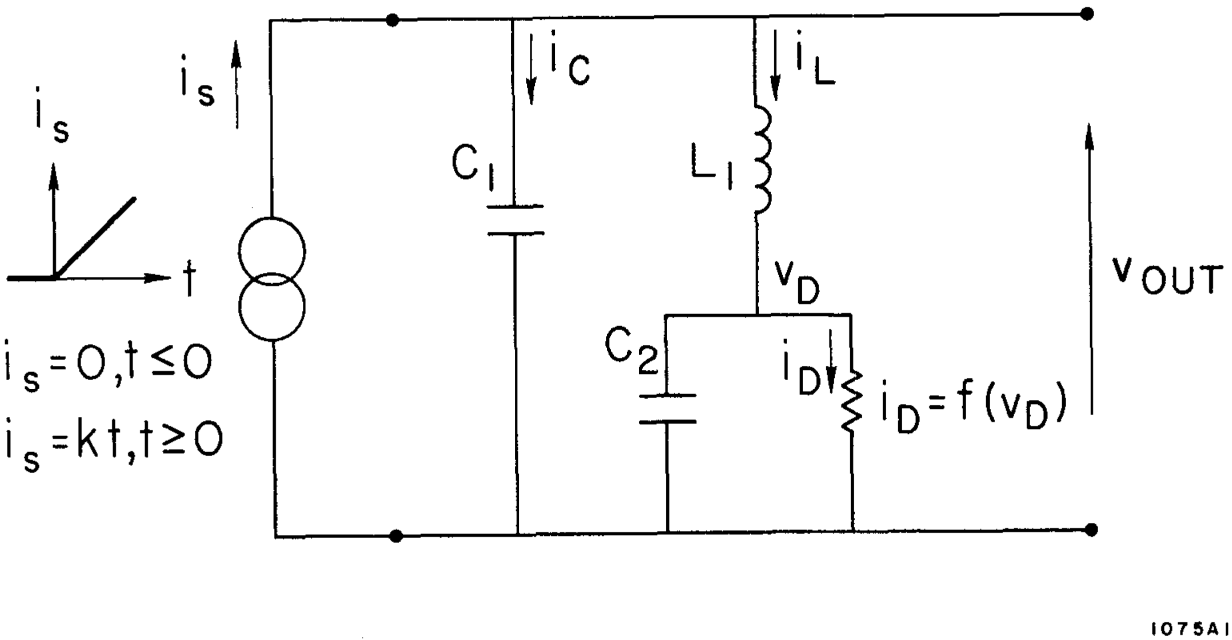


FIG. 1--Tunnel-diode circuitry.

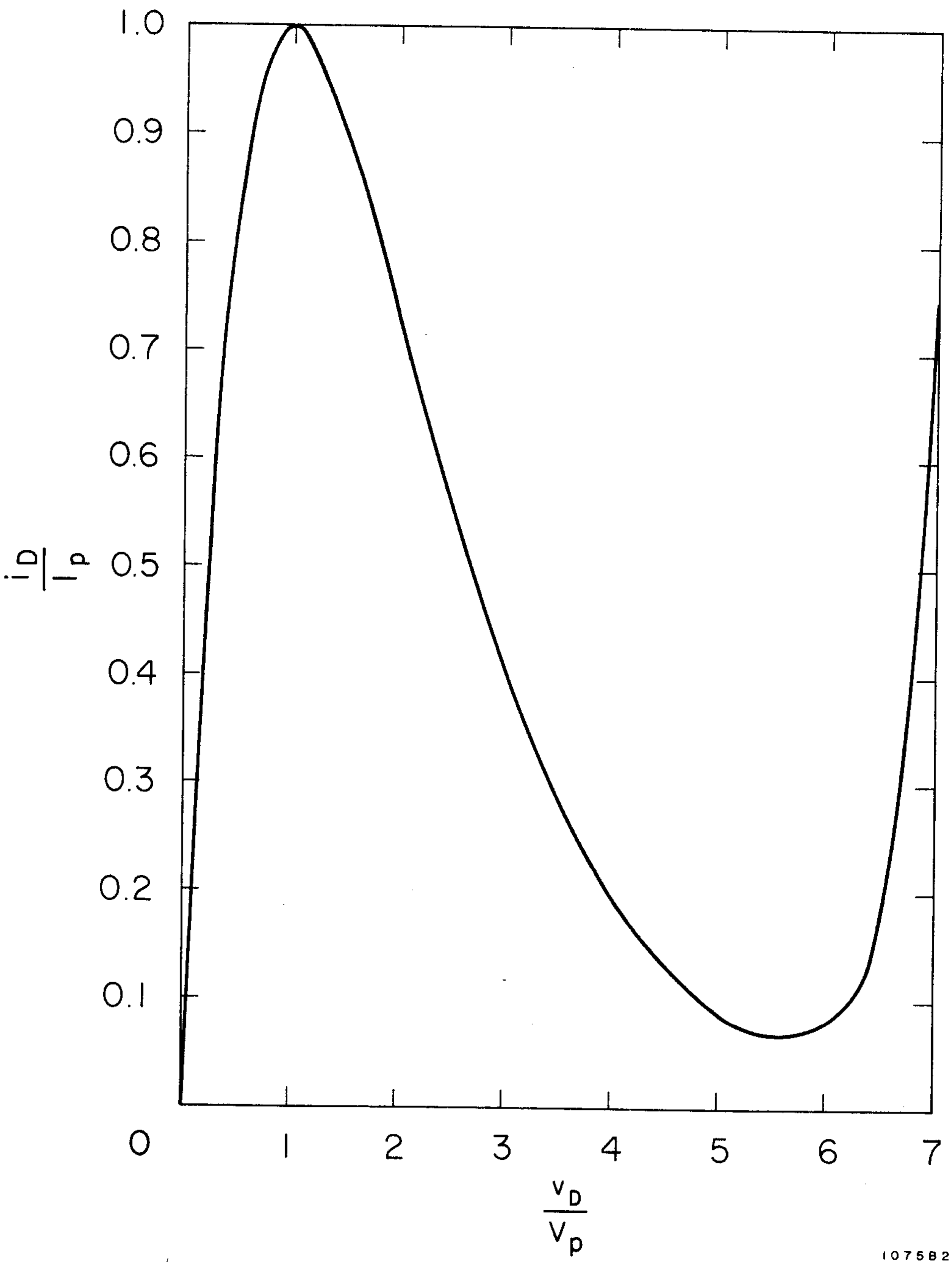


FIG. 2--Tunnel-diode dc current versus voltage characteristic.

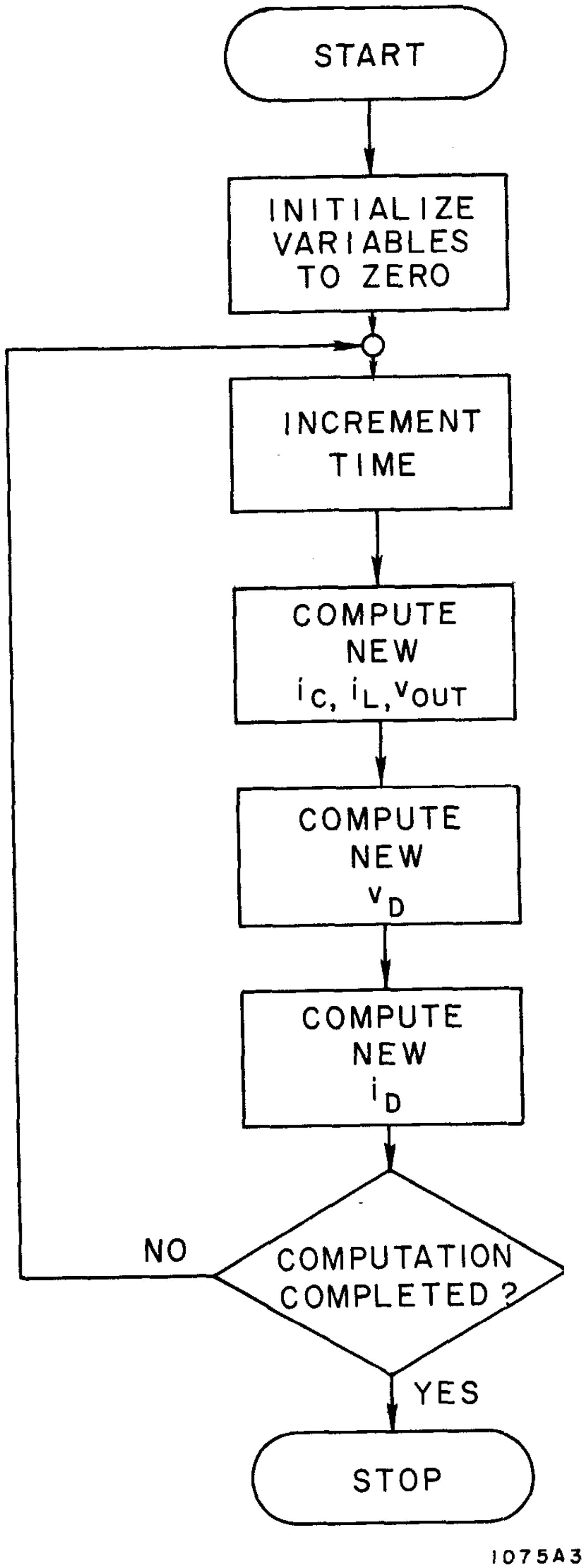


FIG. 3--Flow-chart of the computer program.

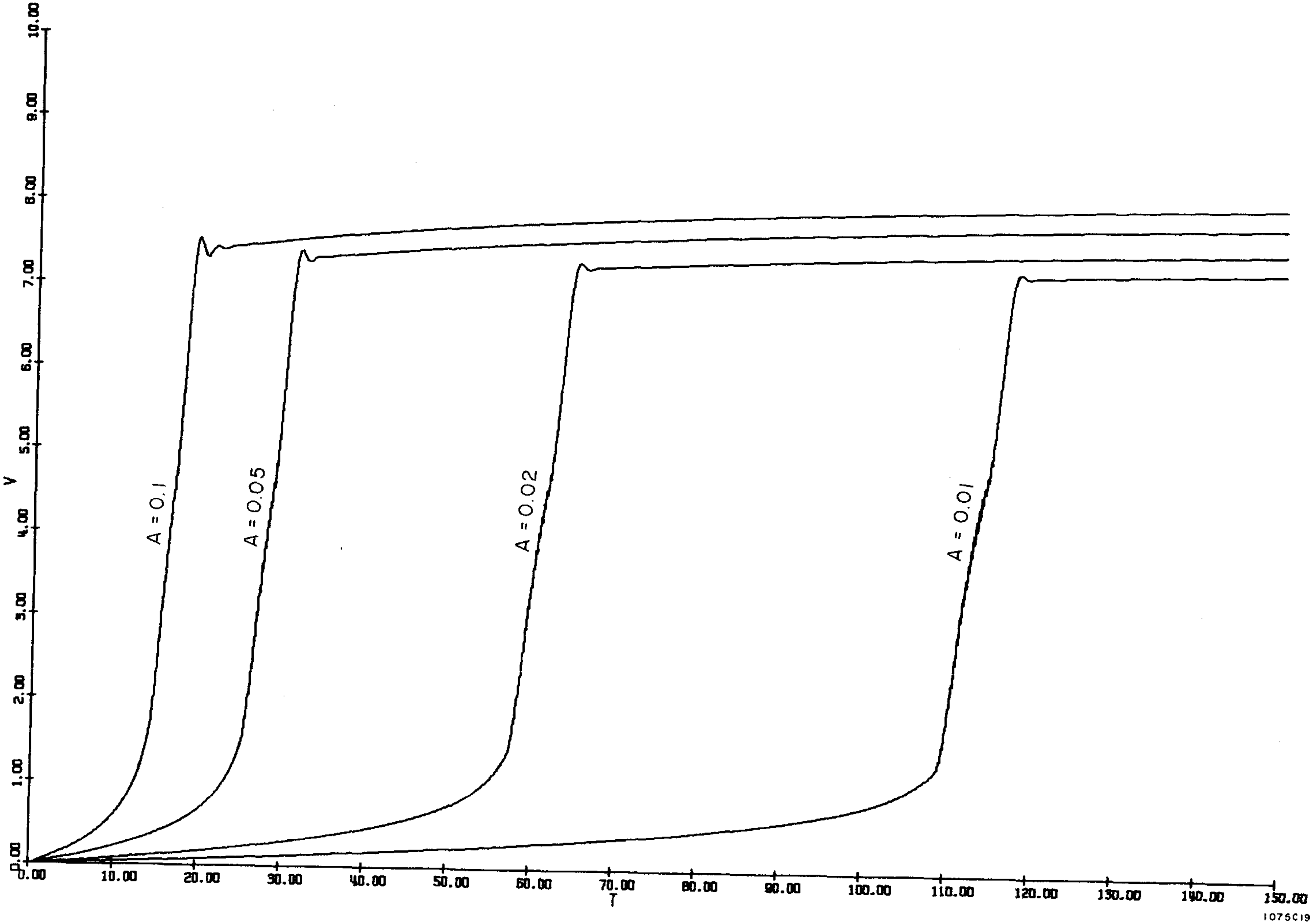


FIG. 4(a)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.02$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.1$.

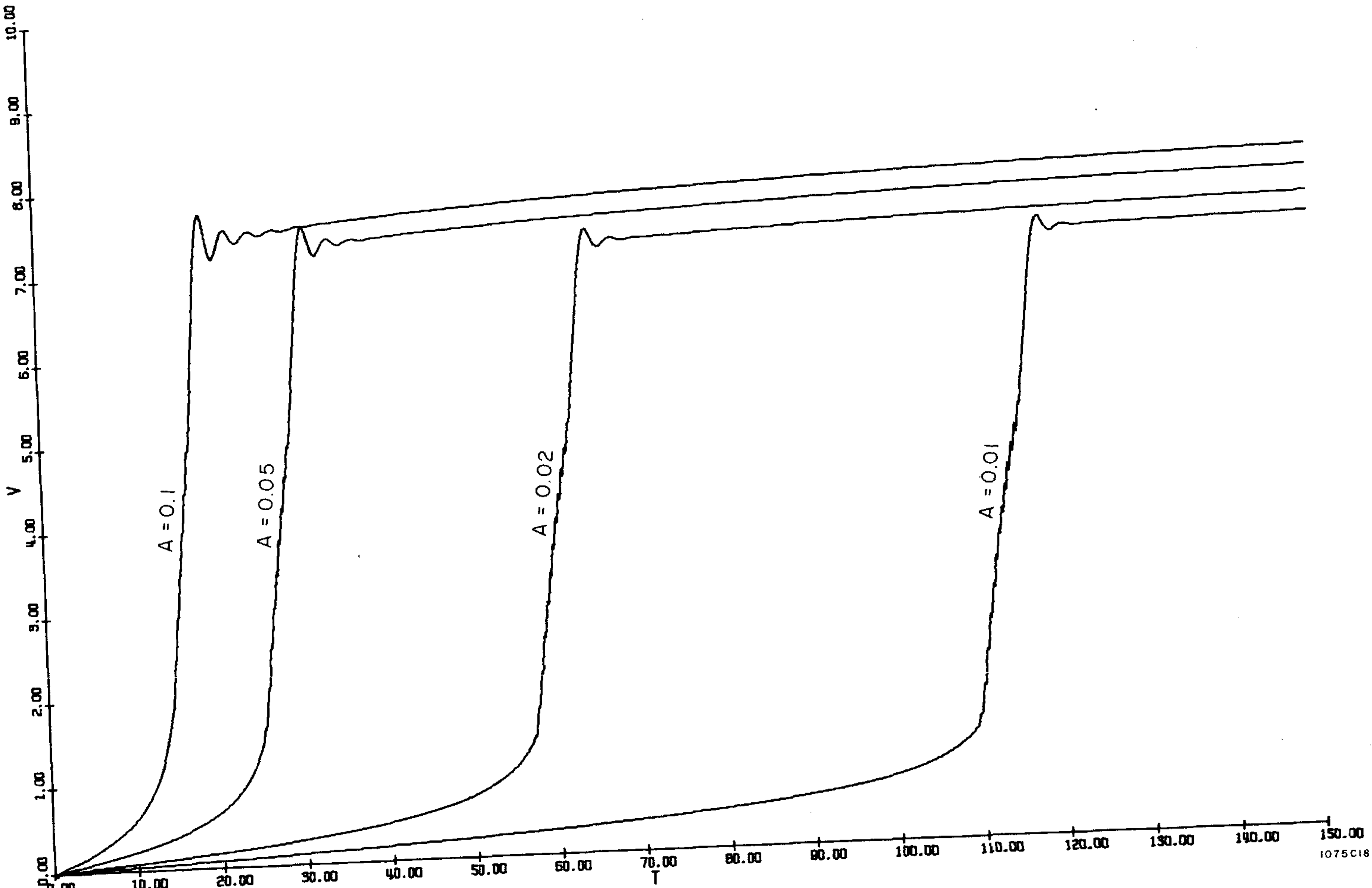


FIG. 4(b)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.02$. Normalized inductance $L \equiv I_p^2 L_1 \Big/ \left(V_p^2 C_1\right) = 0.2$.

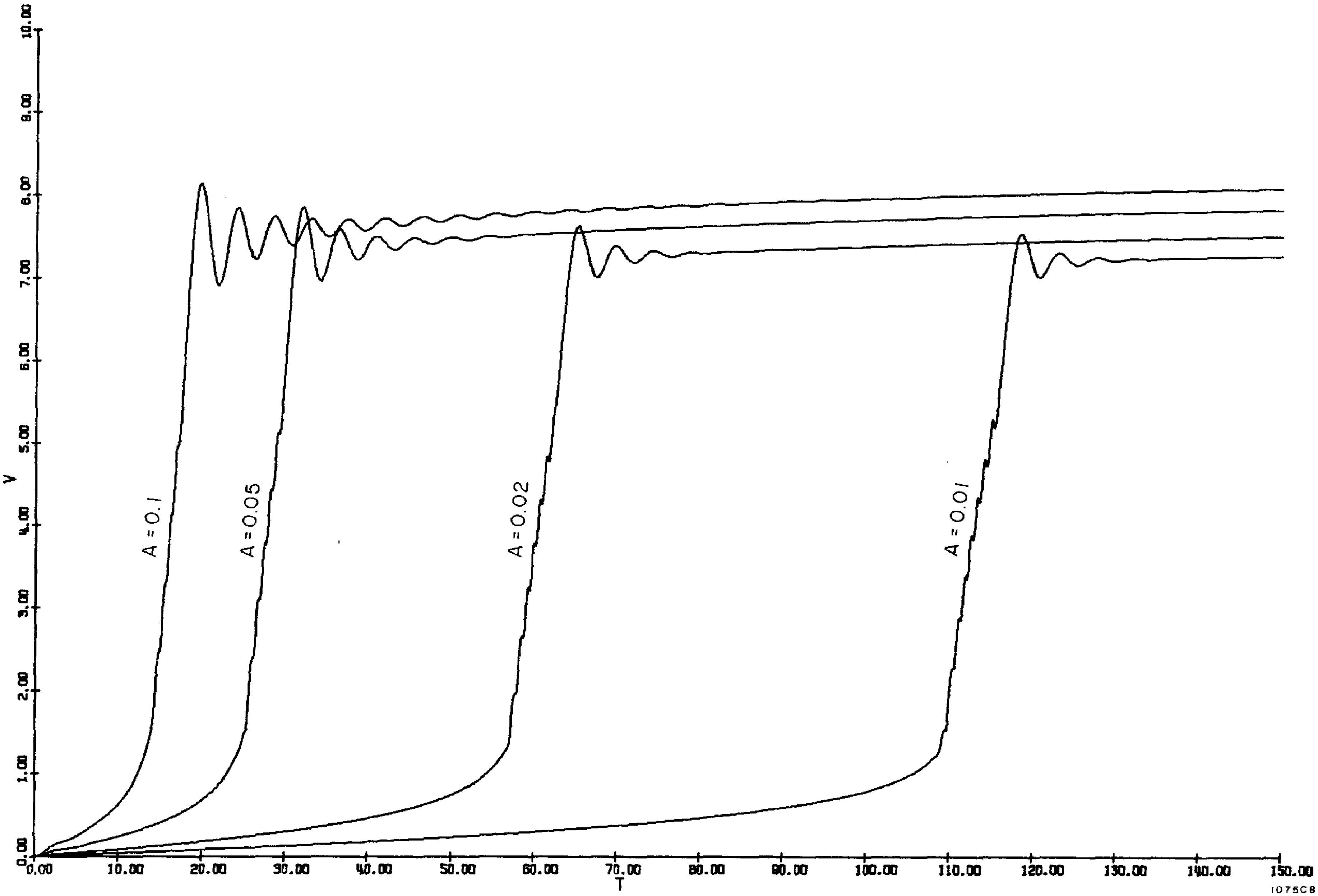


FIG. 4(c)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.02$. Normalized inductance $L \equiv I_p^2 L_1 \Big/ \left(V_p^2 C_1\right) = 0.5$.

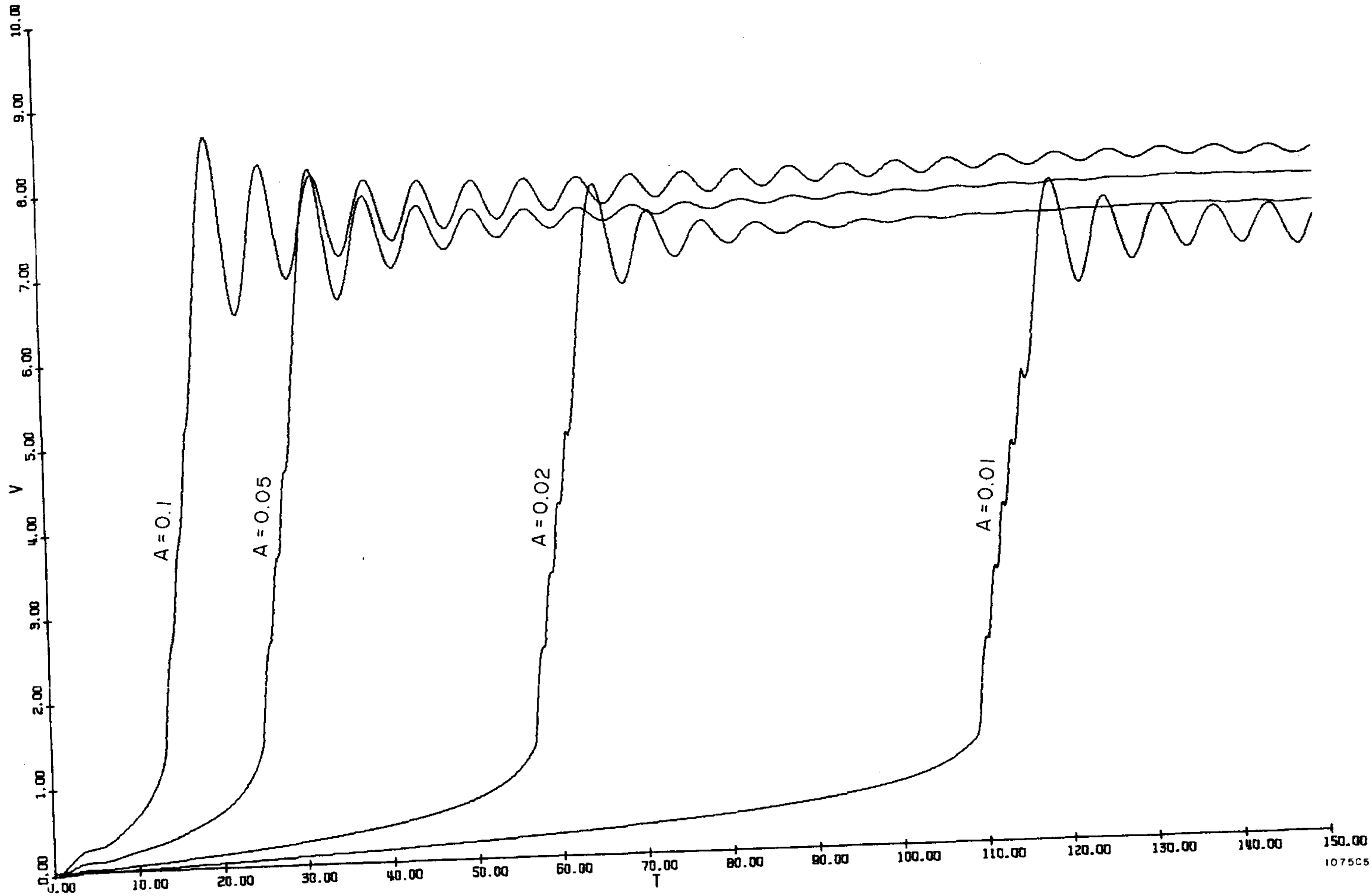


FIG. 4(d)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.02$. Normalized inductance $L \equiv I_p^2 L_1 \Big/ \left(V_p^2 C_1\right) = 1.0$.

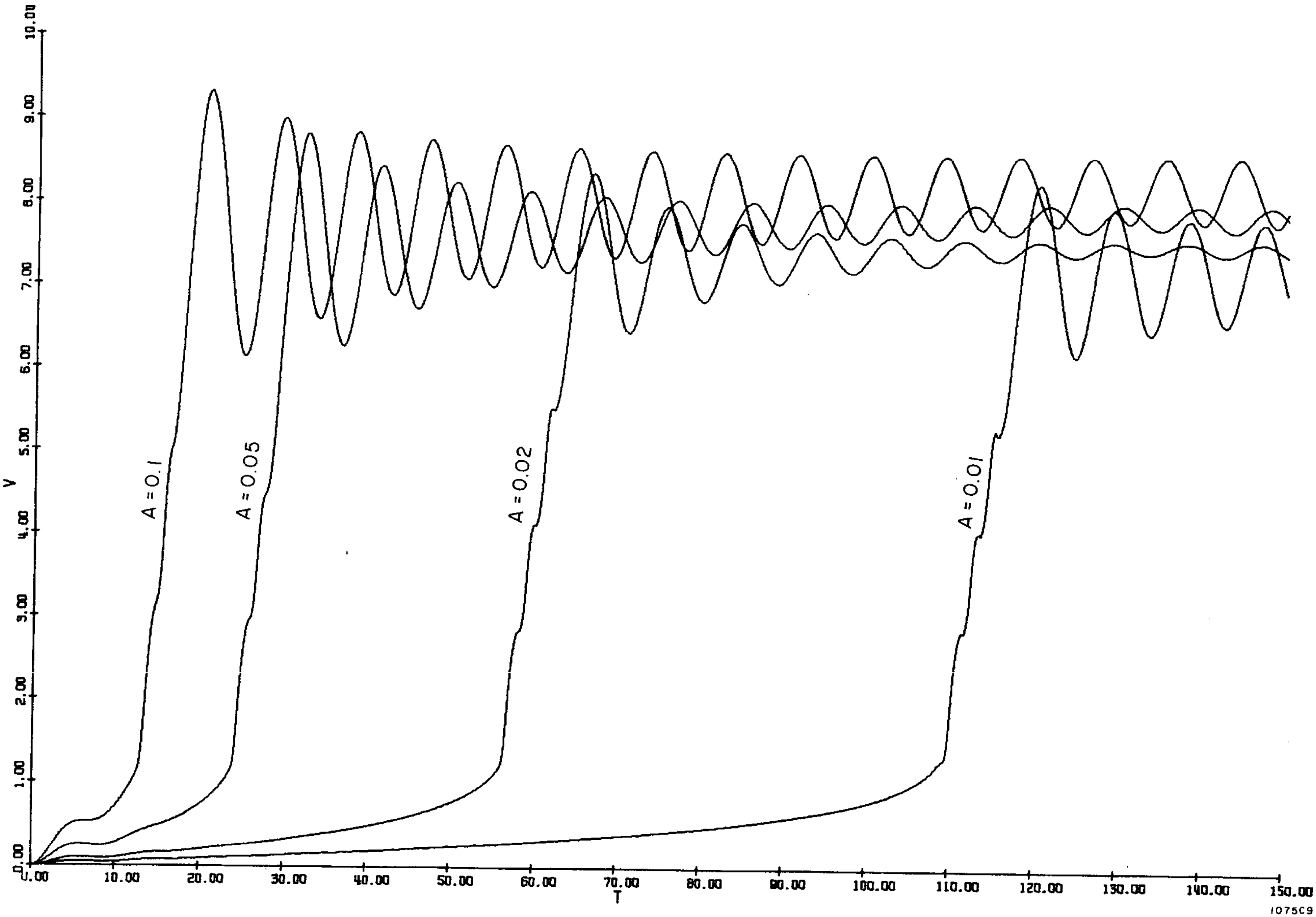


FIG. 4(e)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.02$. Normalized inductance $L \equiv I_p^2 L_1 \Big/ \left(V_p^2 C_1\right) = 2.0$.

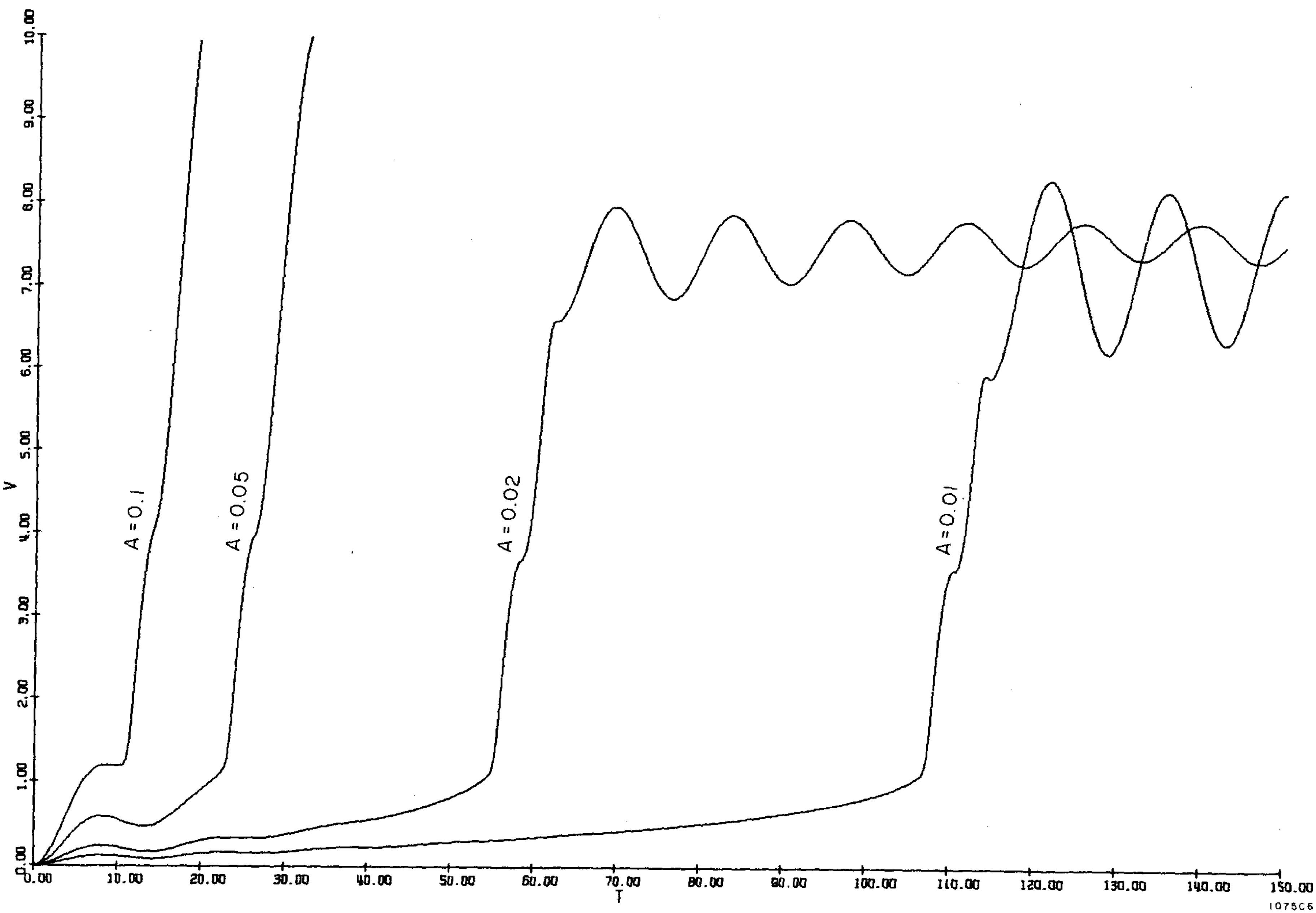


FIG. 4(f)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A = C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.02$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 5.0$.

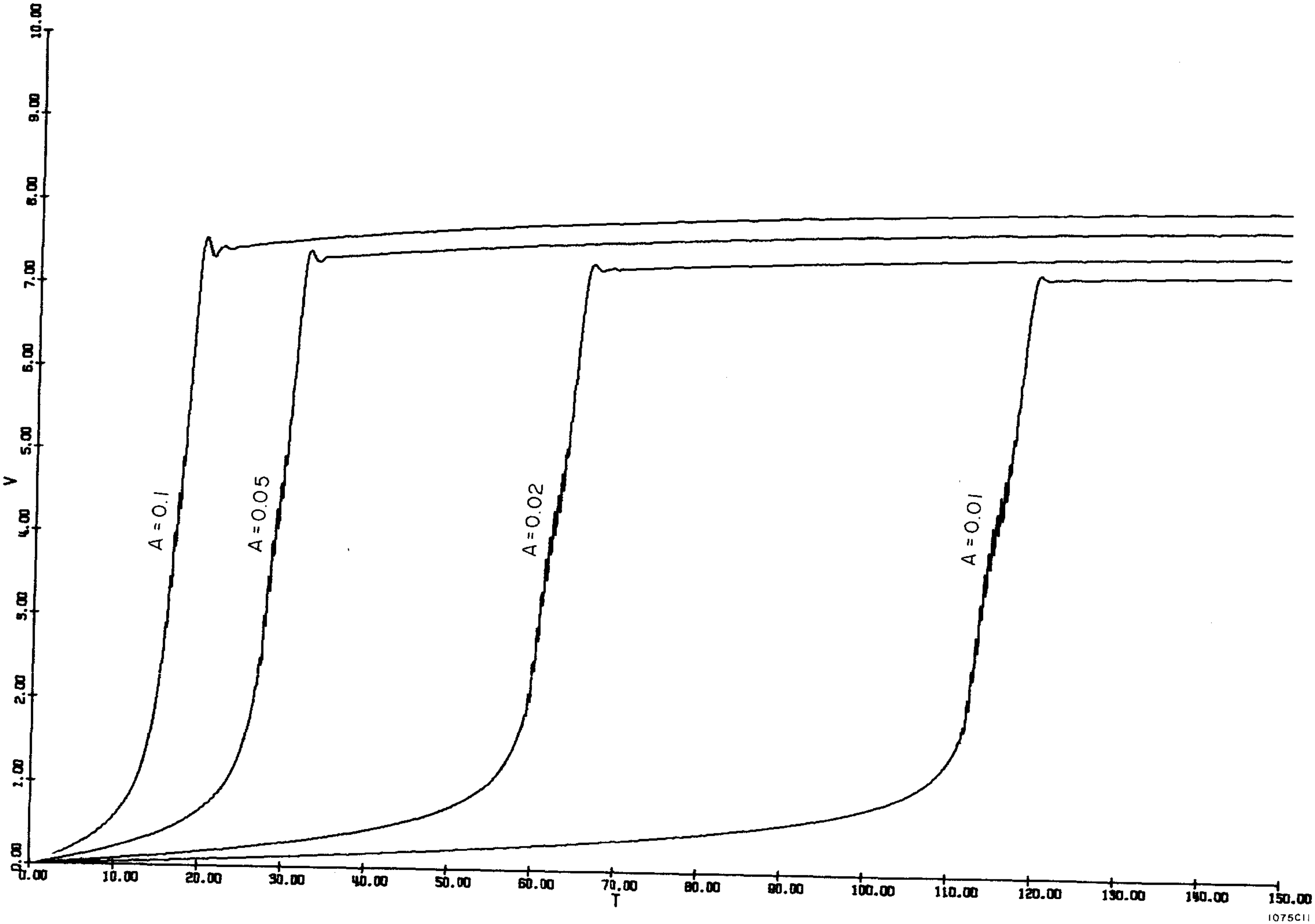


FIG. 5(a)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.05$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.1$.

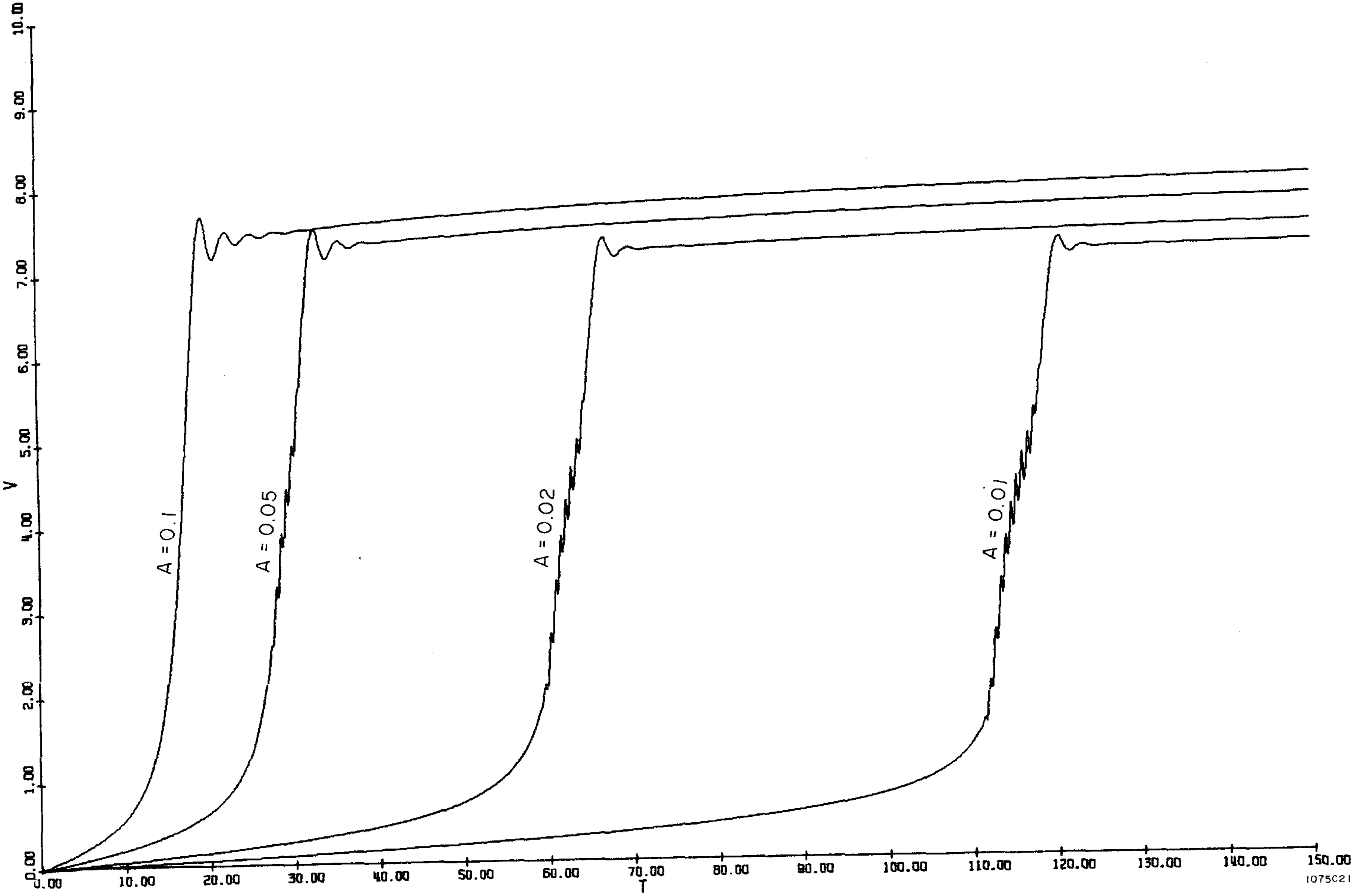


FIG. 5(b)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.05$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.2$.

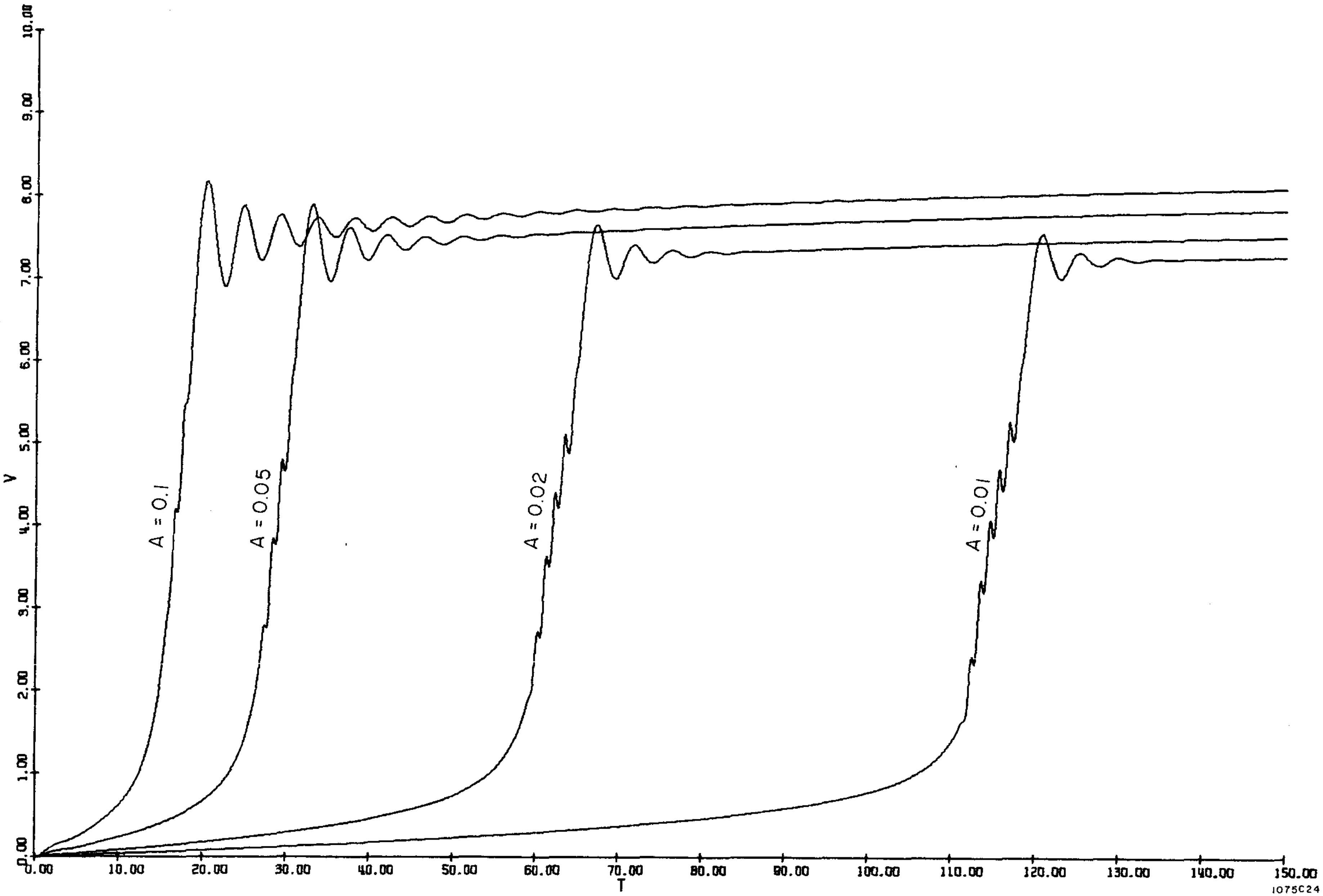


FIG. 5(c)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.05$. Normalized inductance $L \equiv I_p^2 L_1 \Big/ \left(V_p^2 C_1\right) = 0.5$.

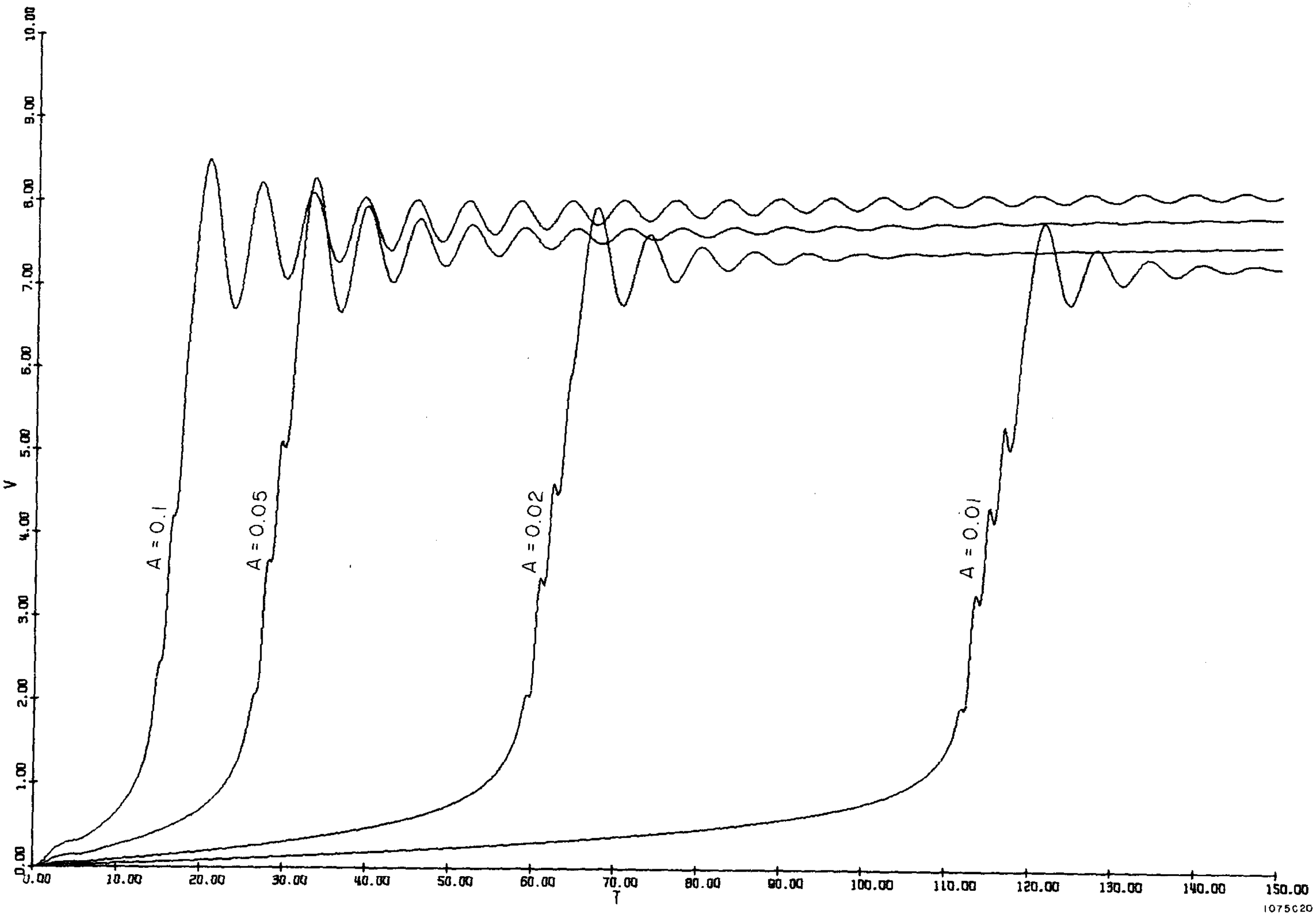
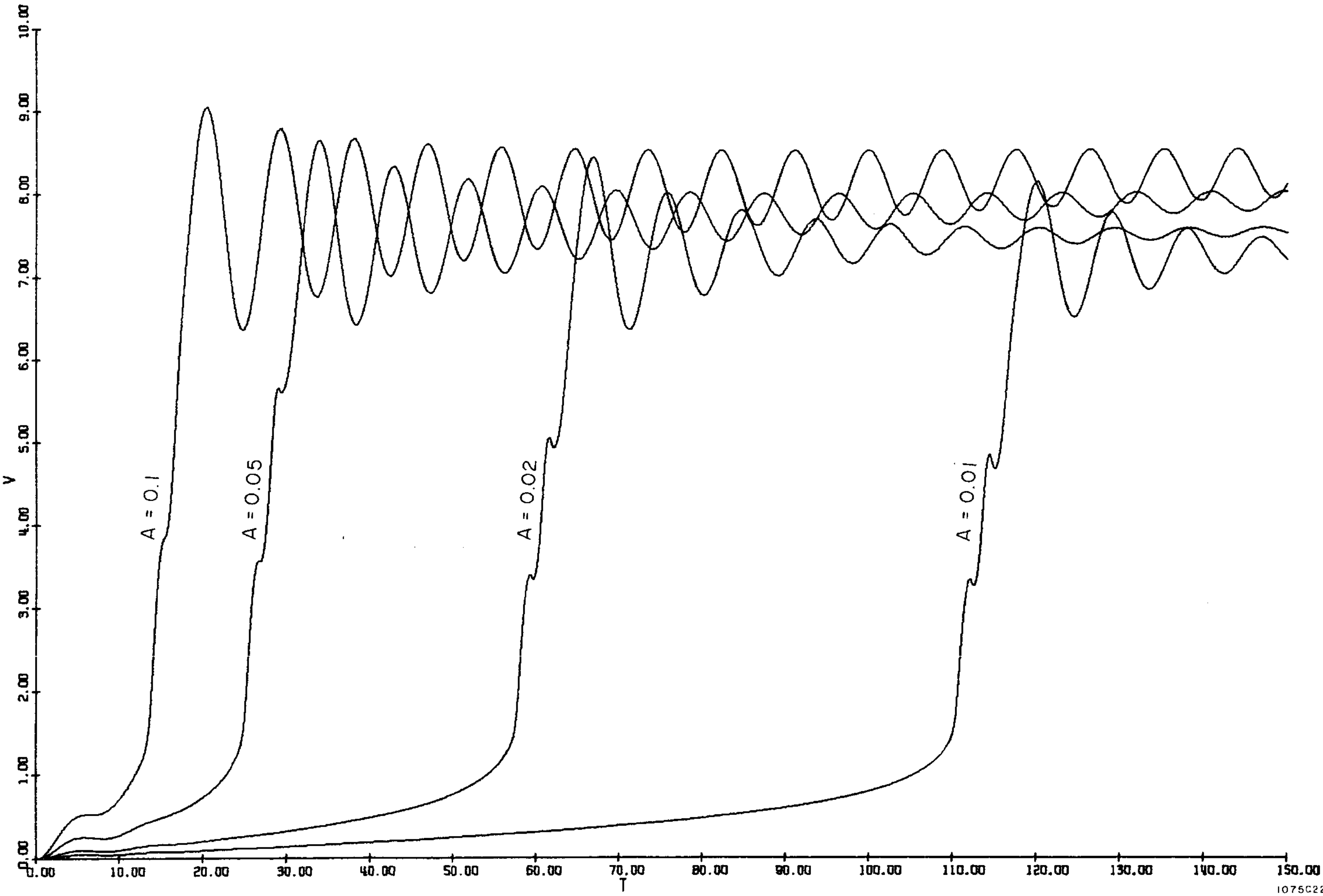


FIG. 5(d)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k / I_p^2$ as parameter for $C_2/C_1 = 0.05$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 1.0$.



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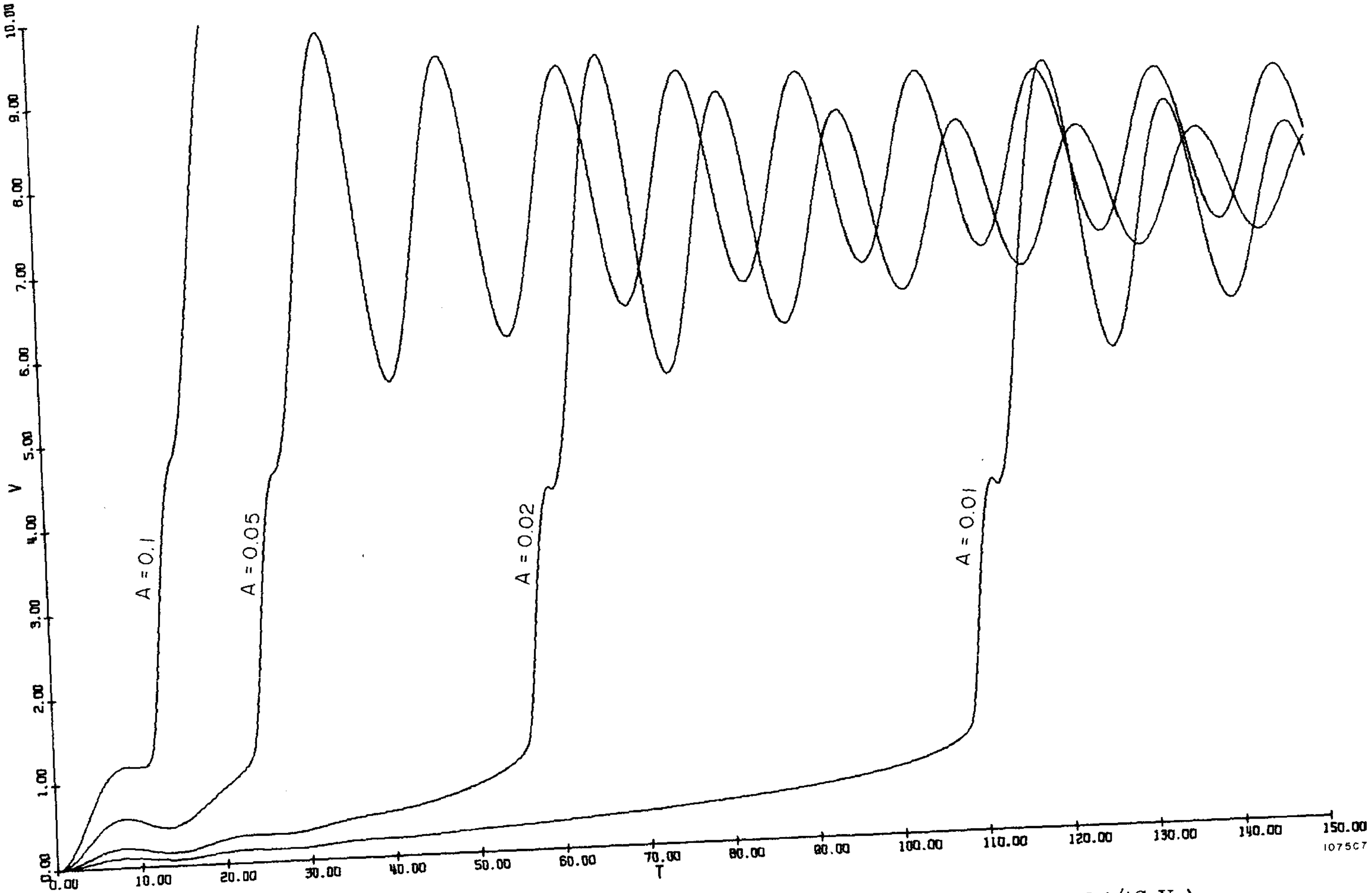


FIG. 5(f)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.05$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 5.0$.

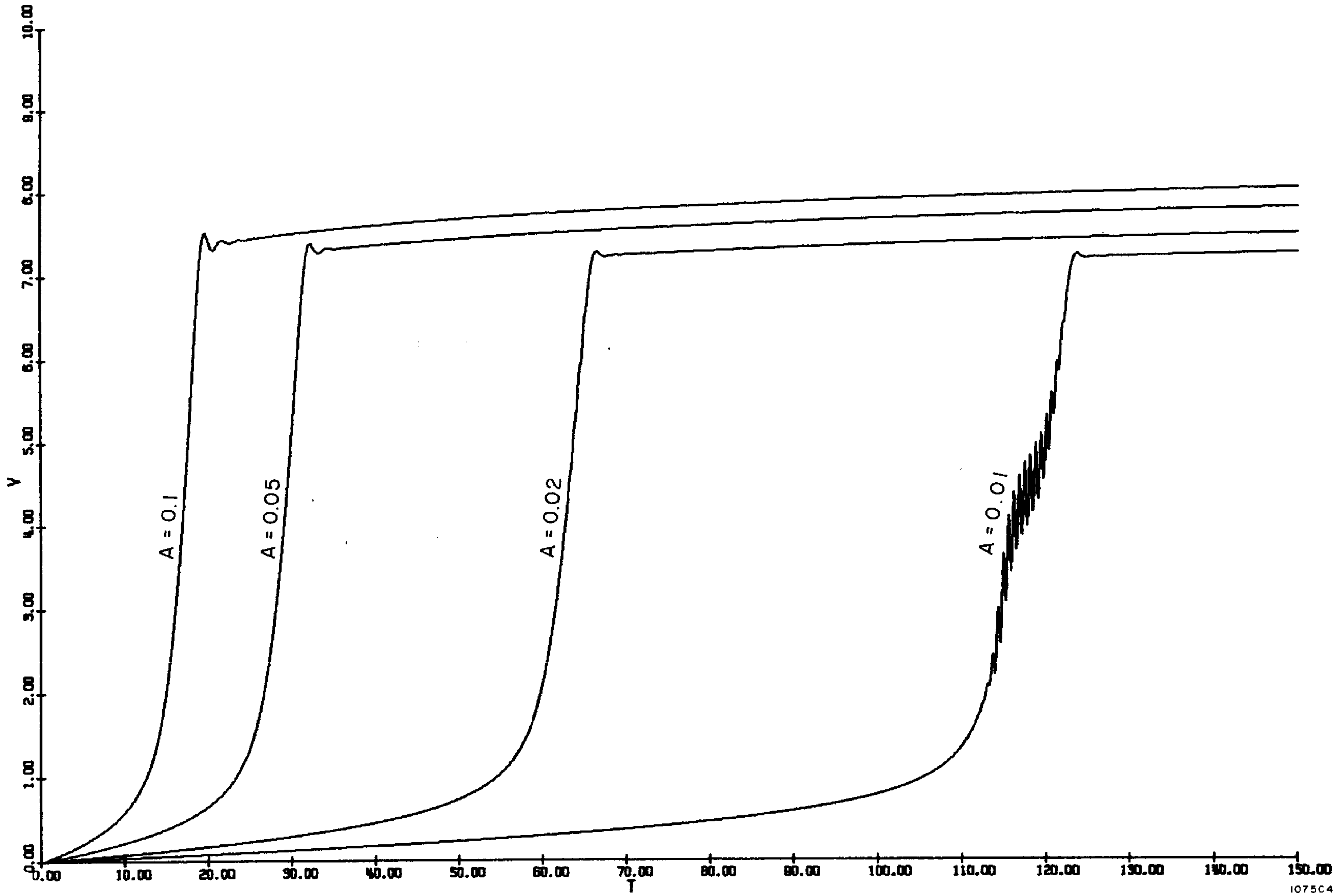


FIG. 6(a)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.1$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.1$.

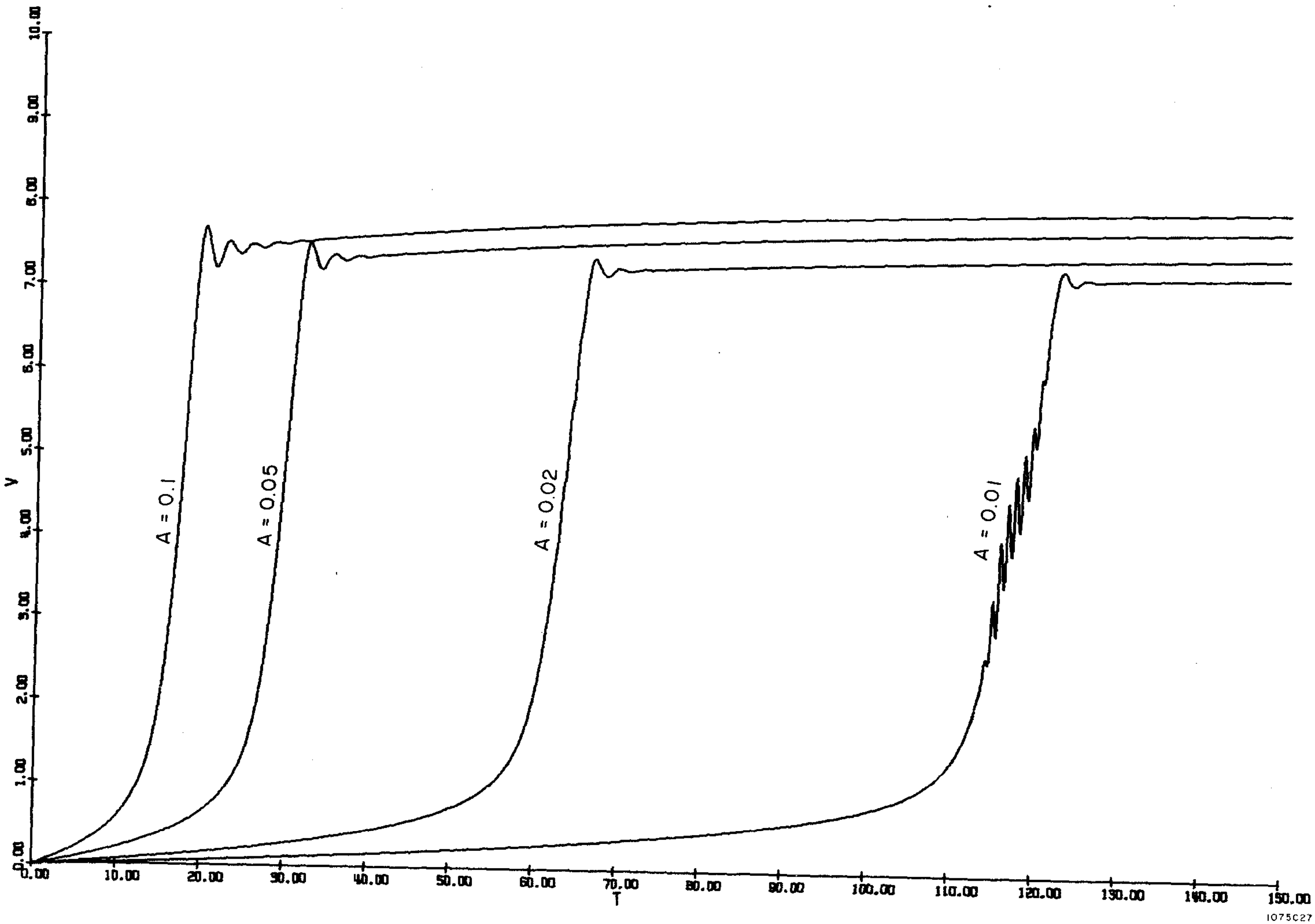


FIG. 6(b)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.1$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.2$.

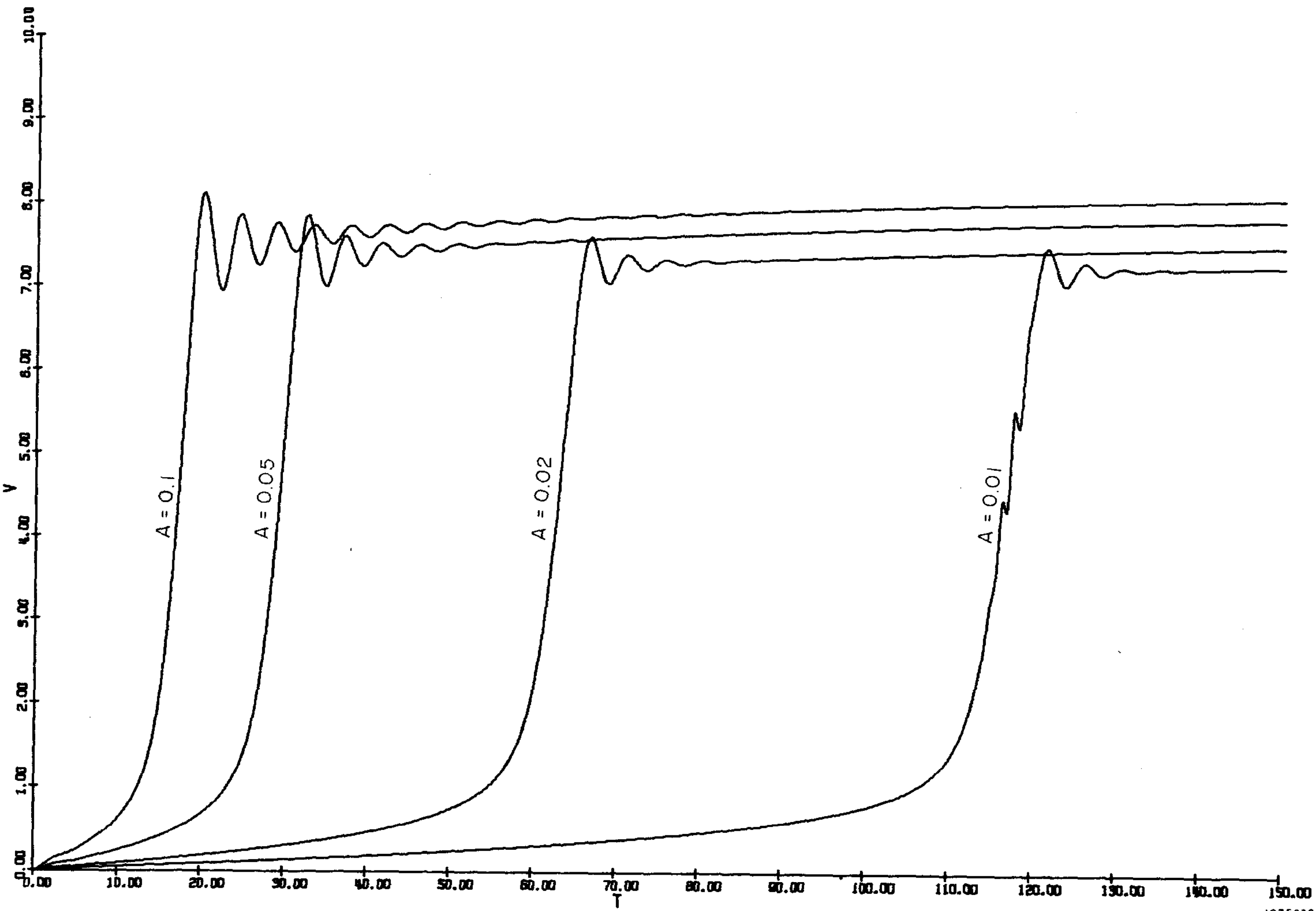
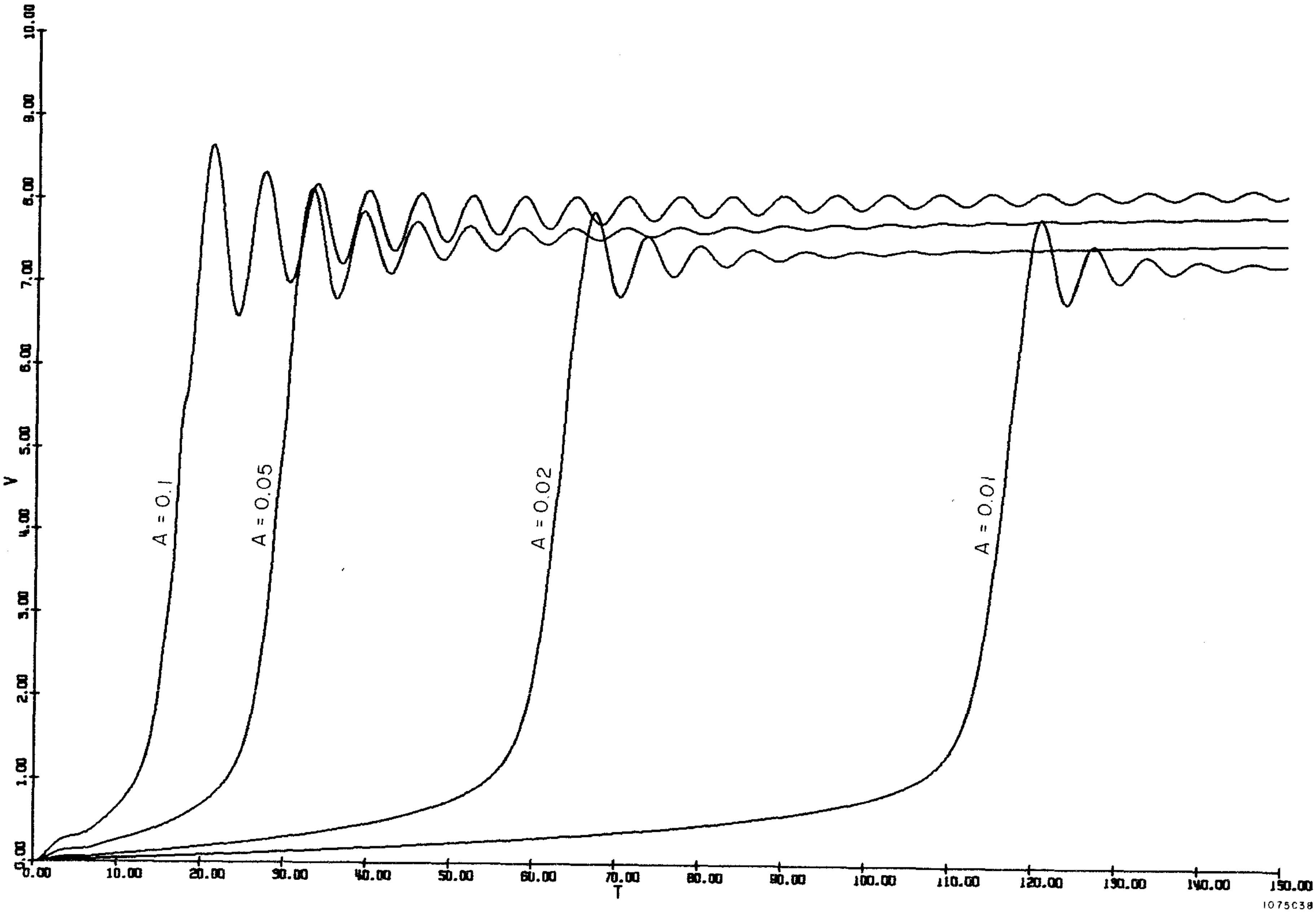


FIG. 6(c)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.1$. Normalized inductance $L \equiv I_p^2 L_1 \big/ \left(V_p^2 C_1\right) = 0.5$.



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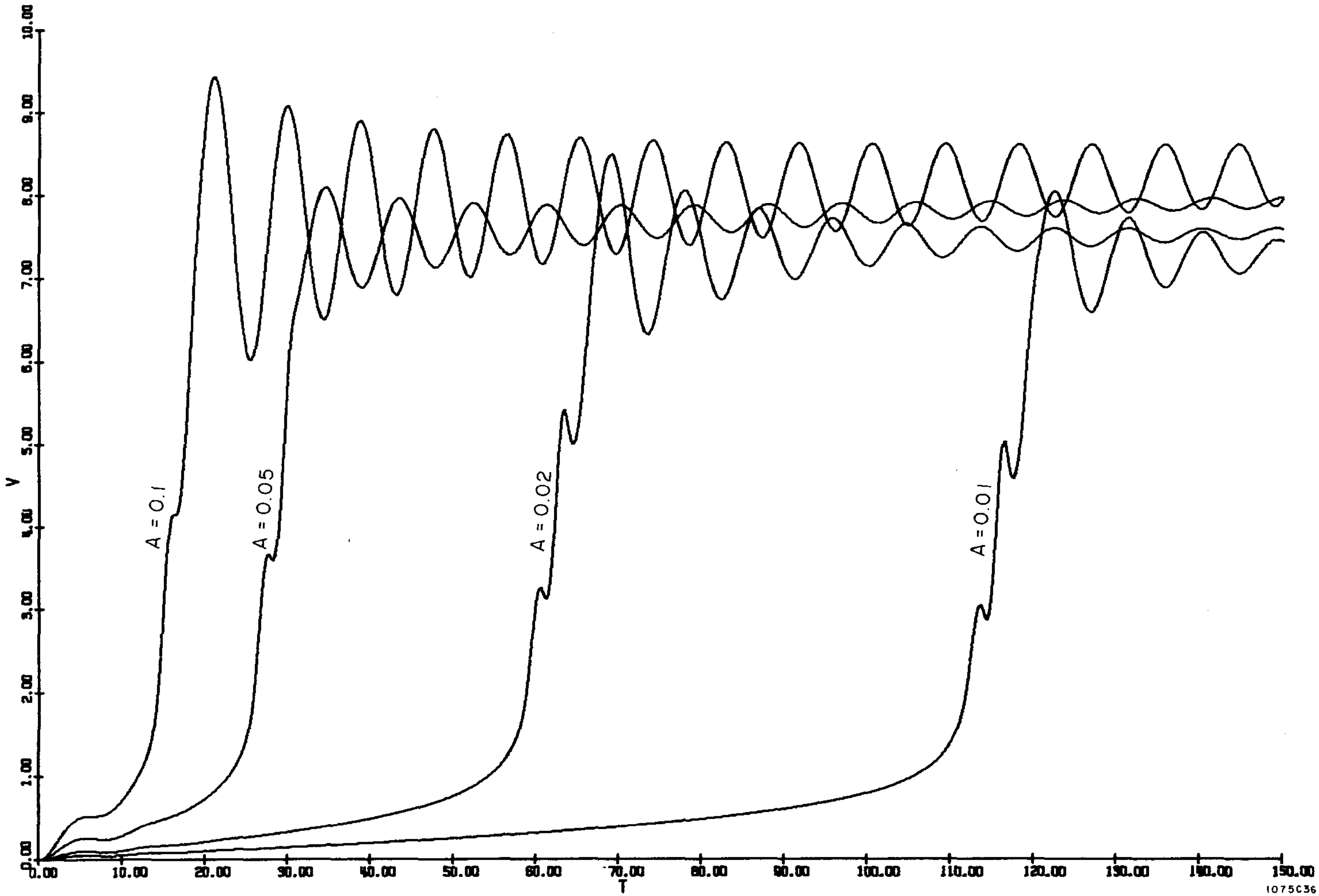

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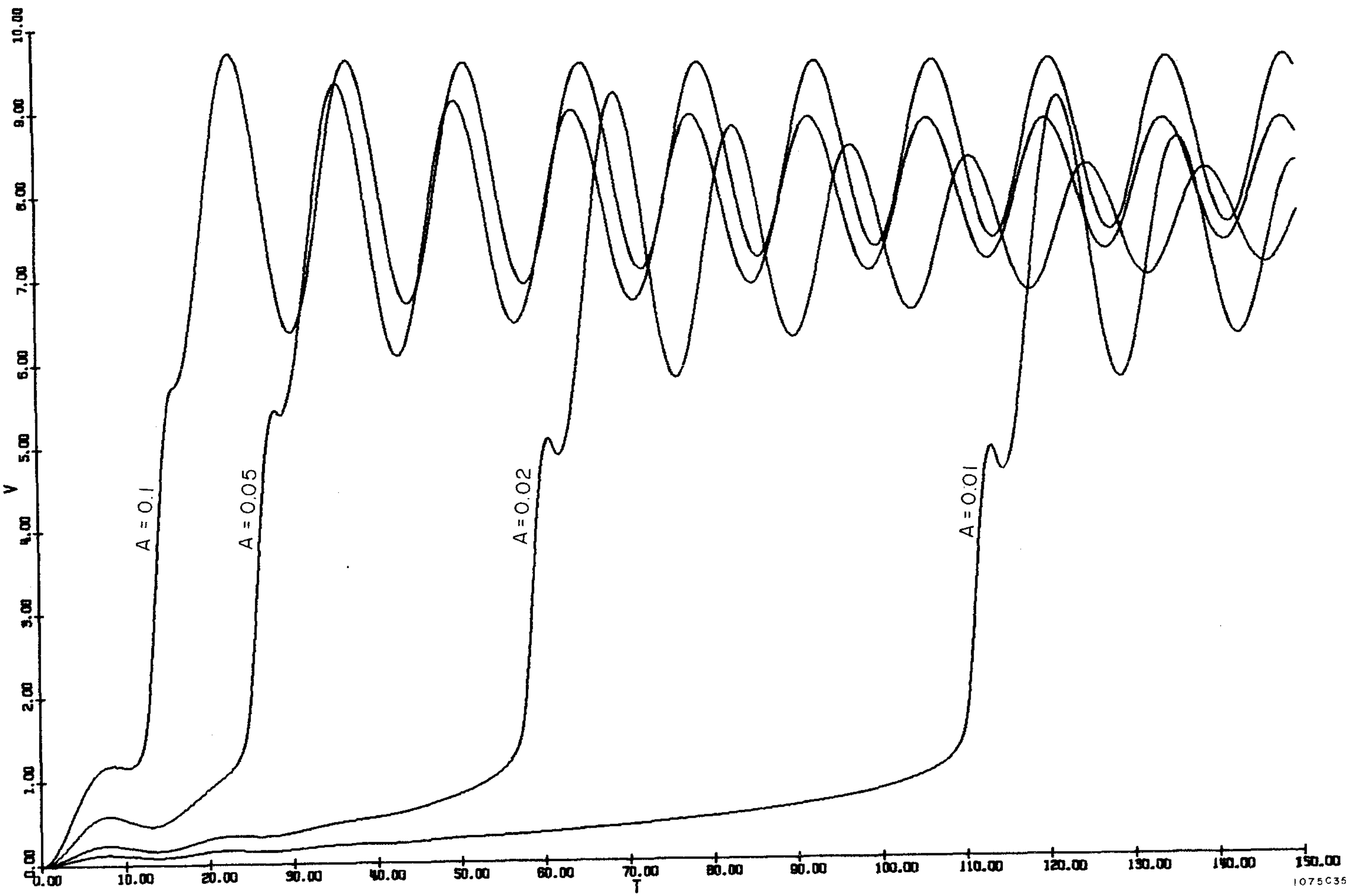

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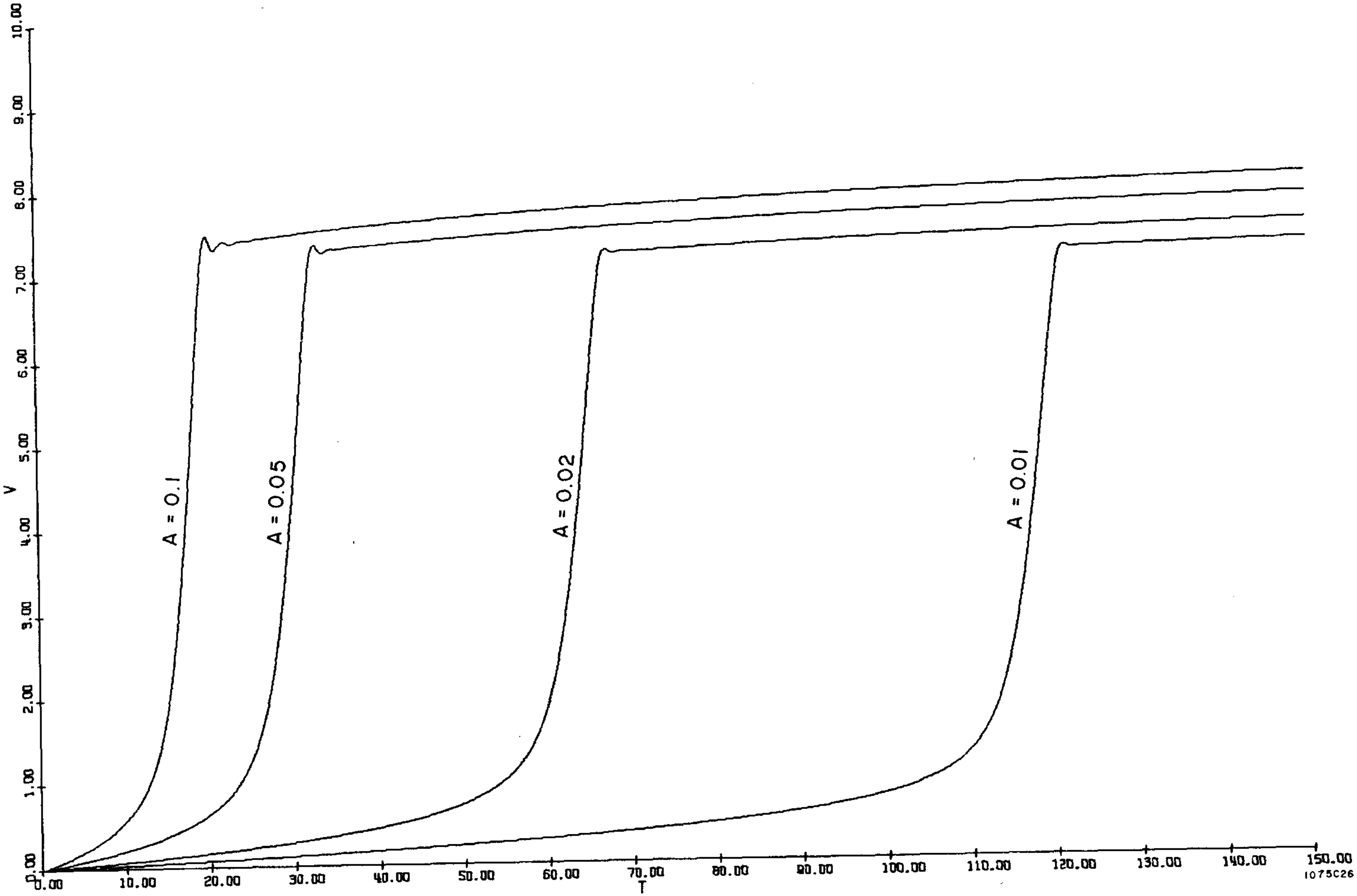
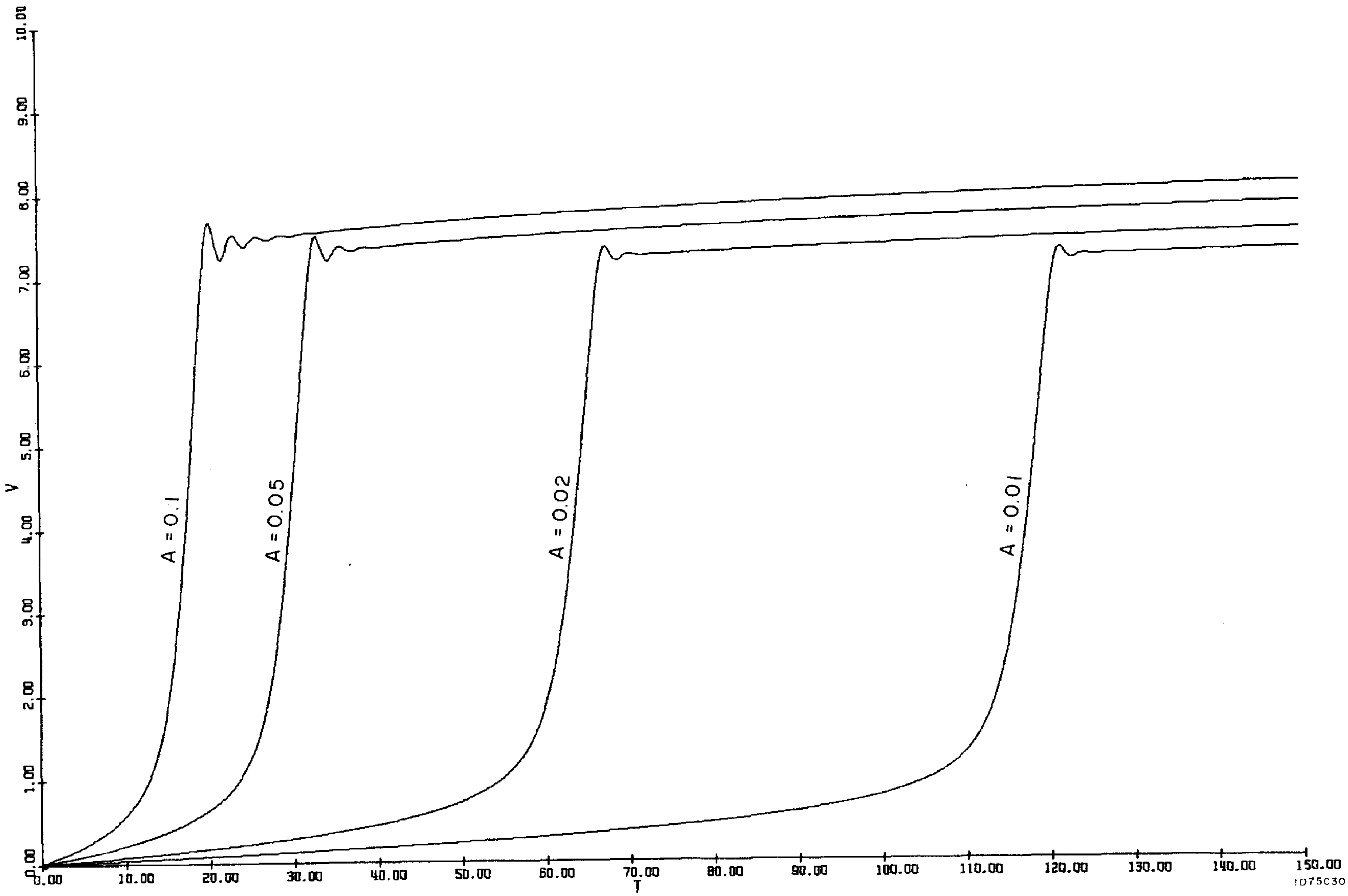


FIG. 7(a)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.2$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.1$.



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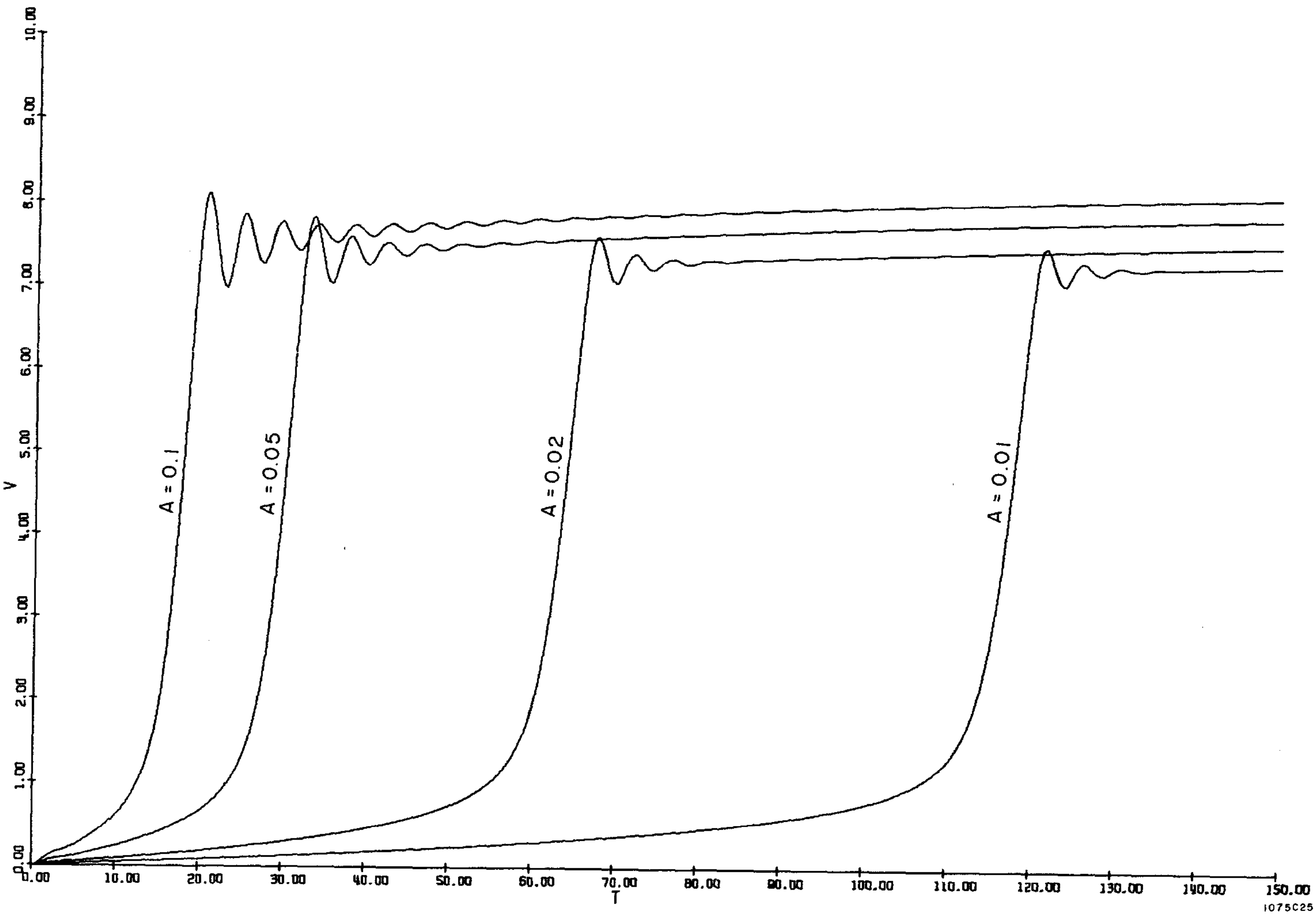

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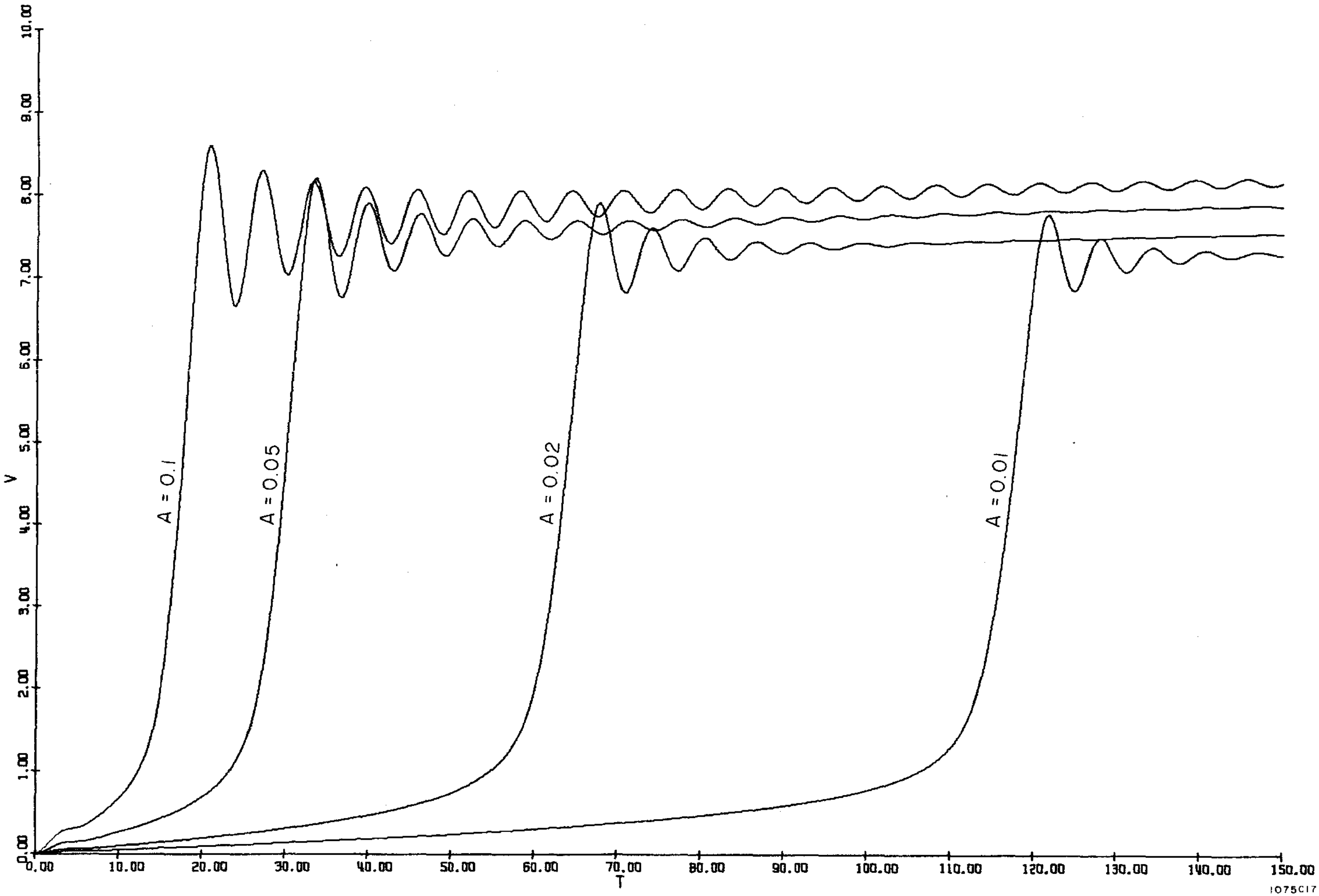
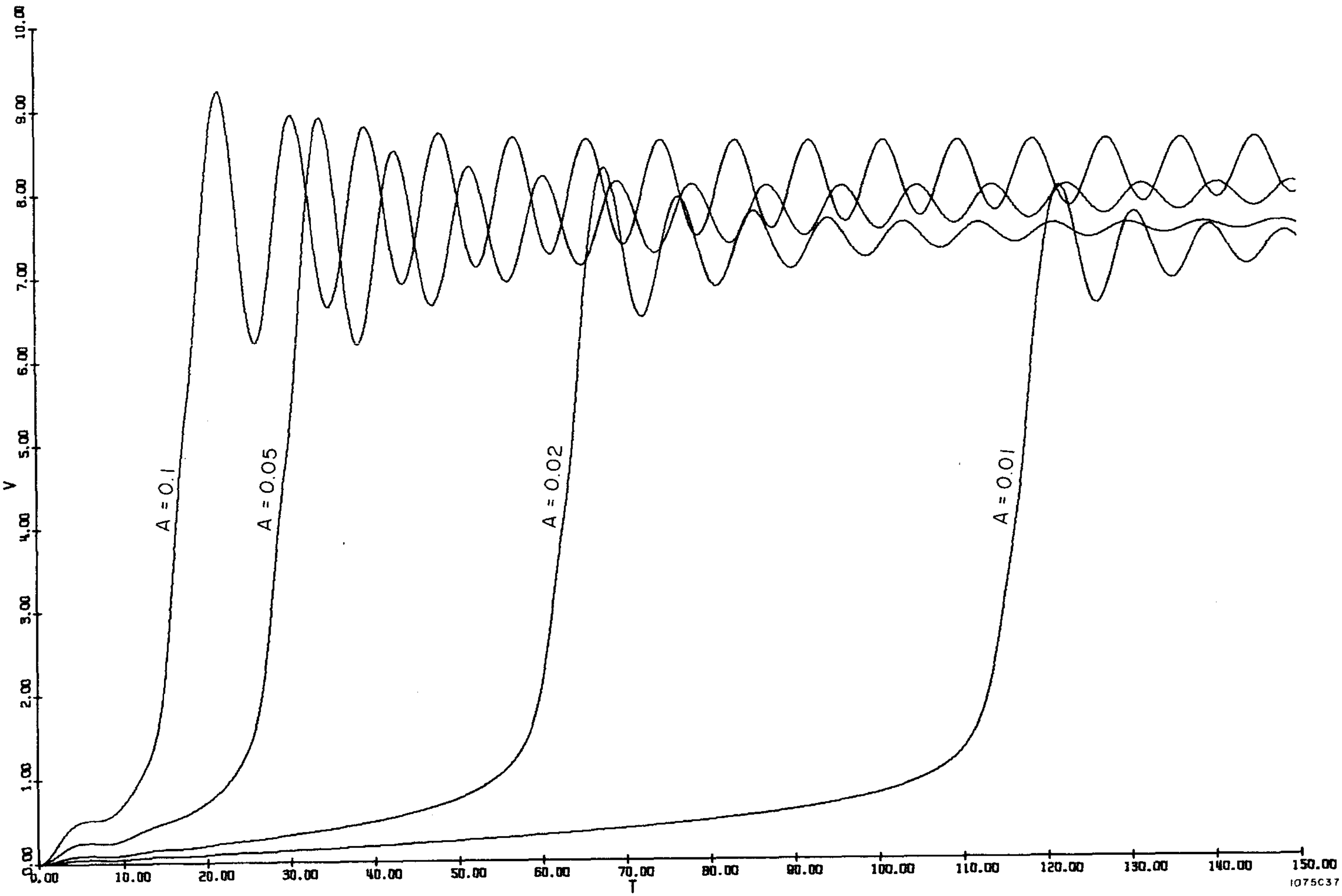


FIG. 7(d)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.2$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 1.0$.



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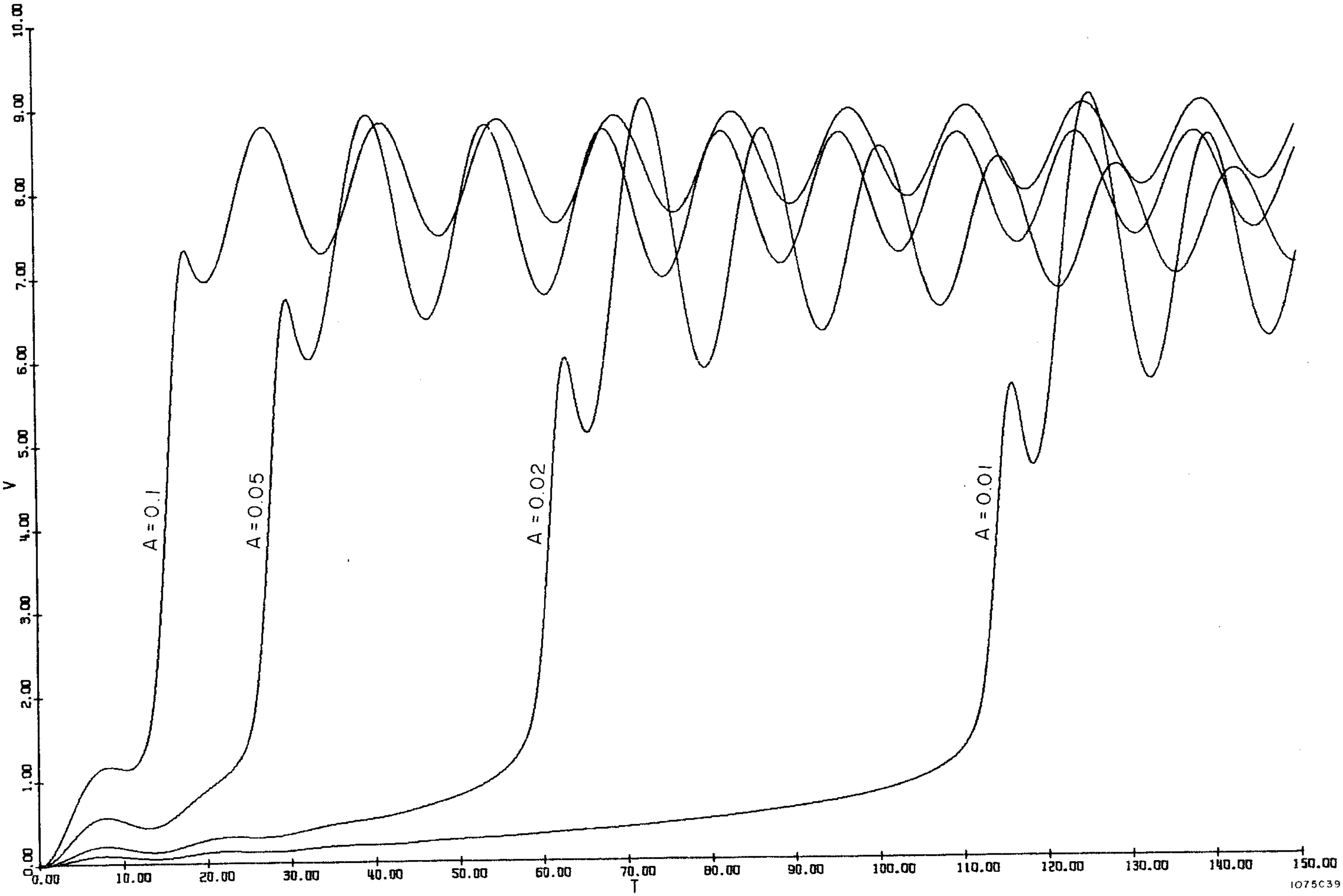

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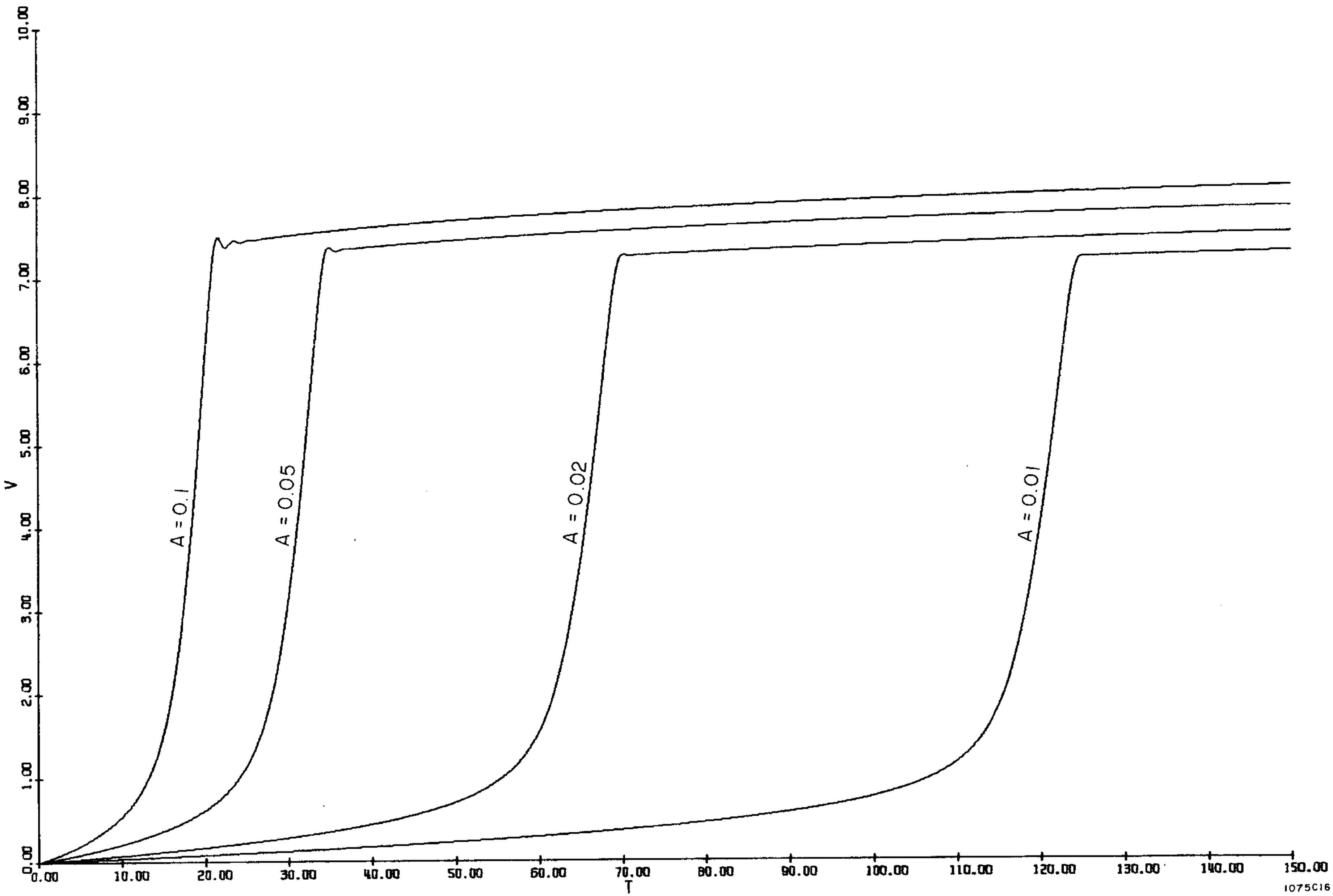


FIG. 8(a)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.5$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.1$.

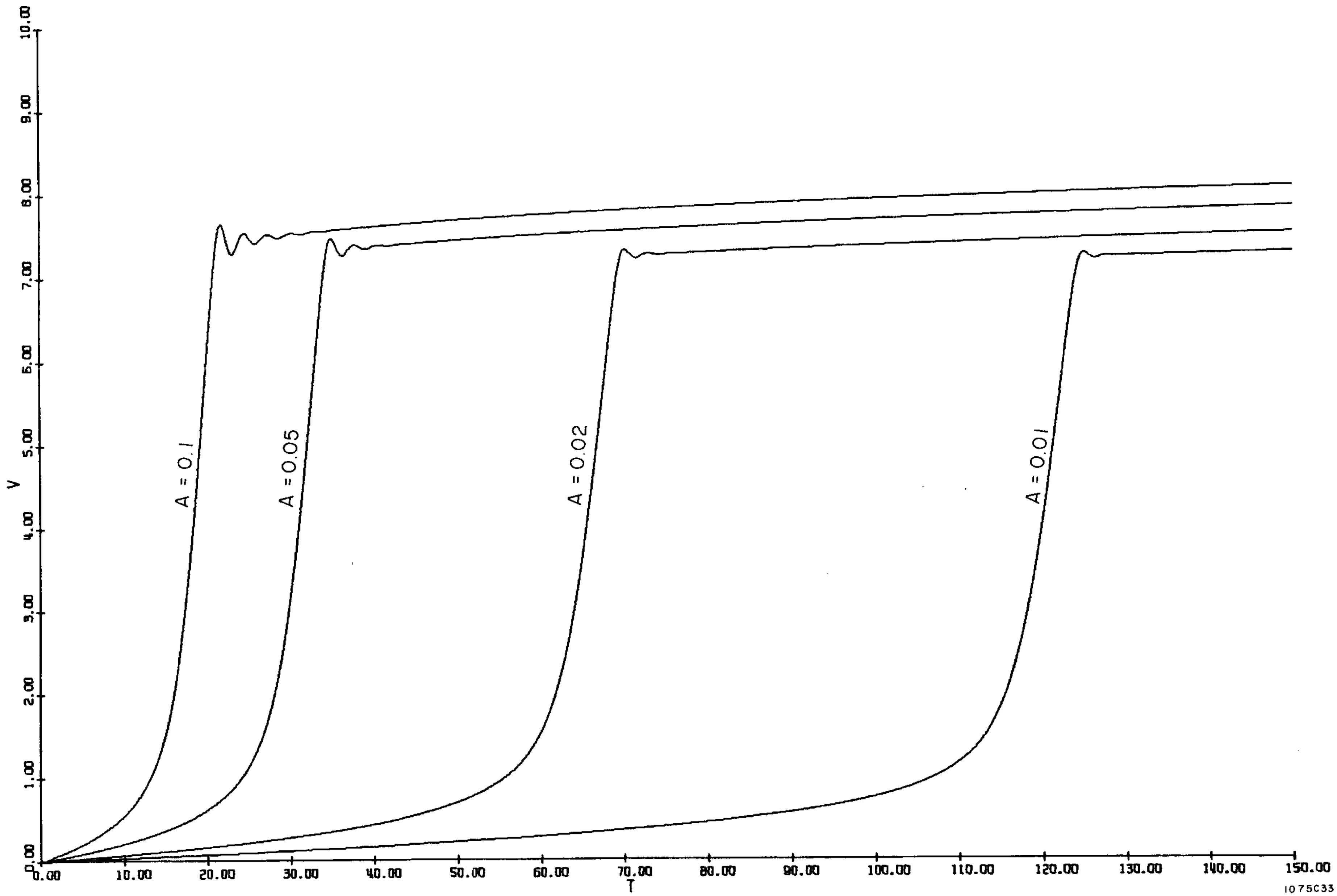


FIG. 8(b)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.5$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.2$.

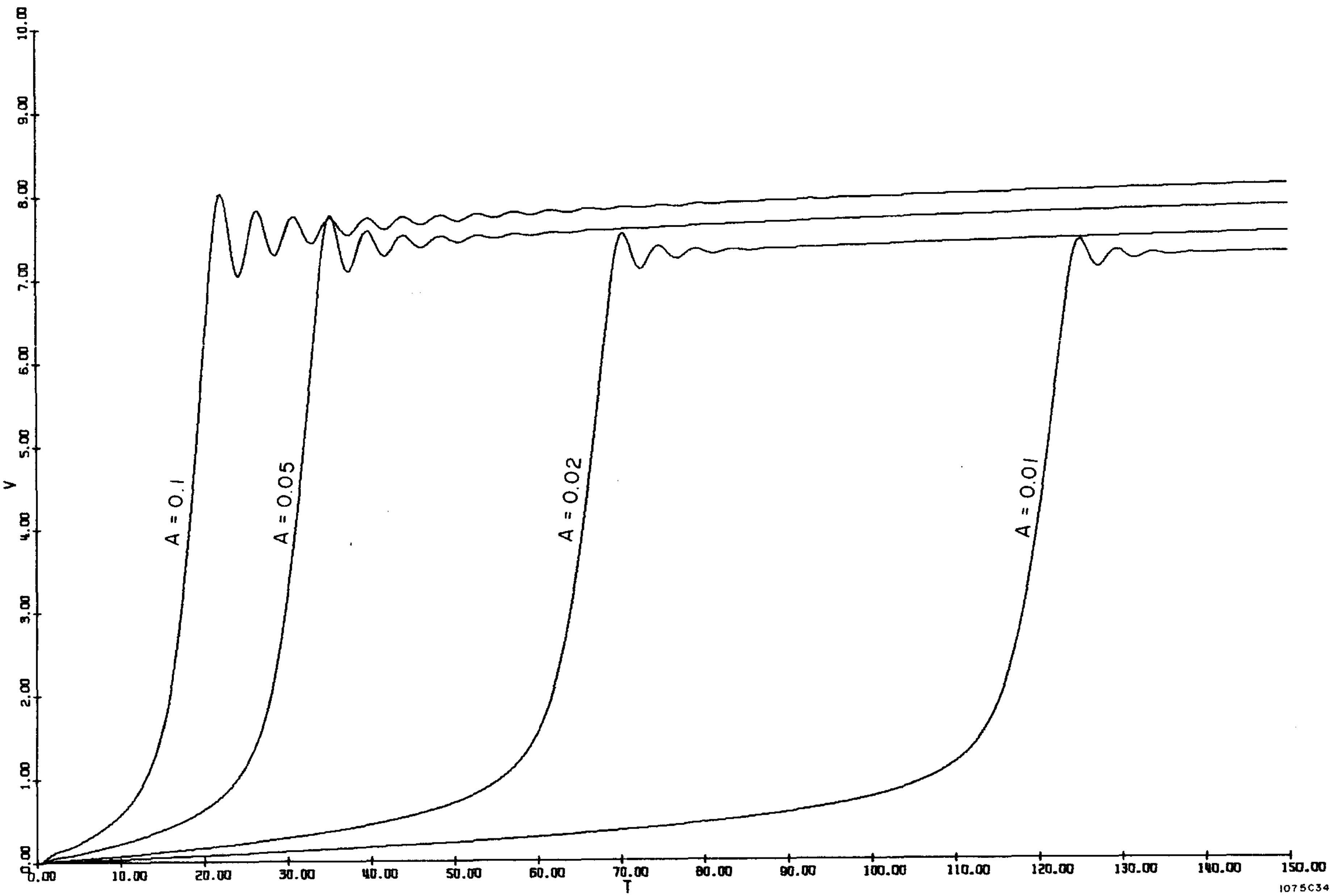
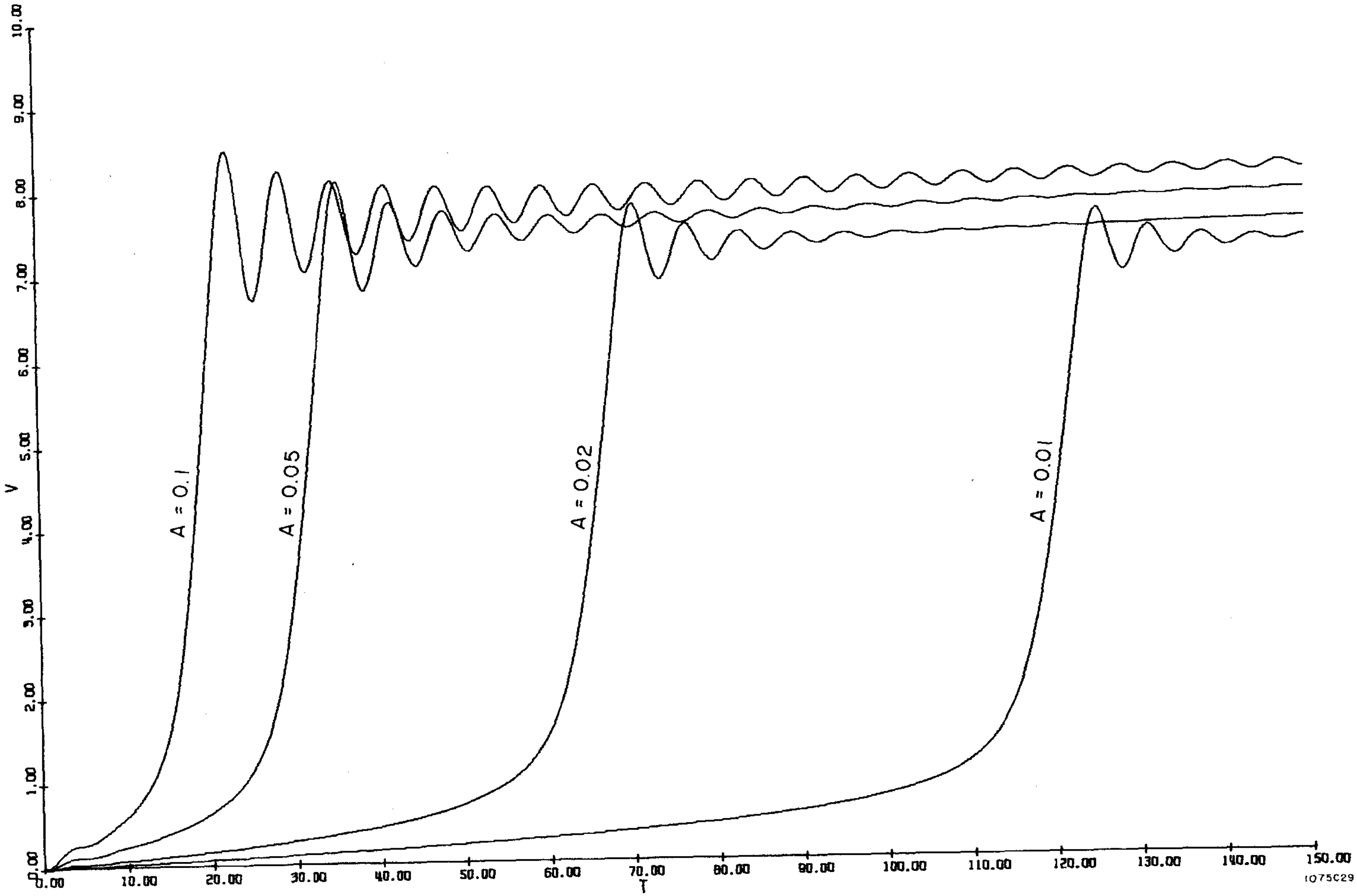


FIG. 8(c)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.5$. Normalized inductance $L \equiv I_p^2 L_1 \big/ \left(V_p^2 C_1\right) = 0.5$.



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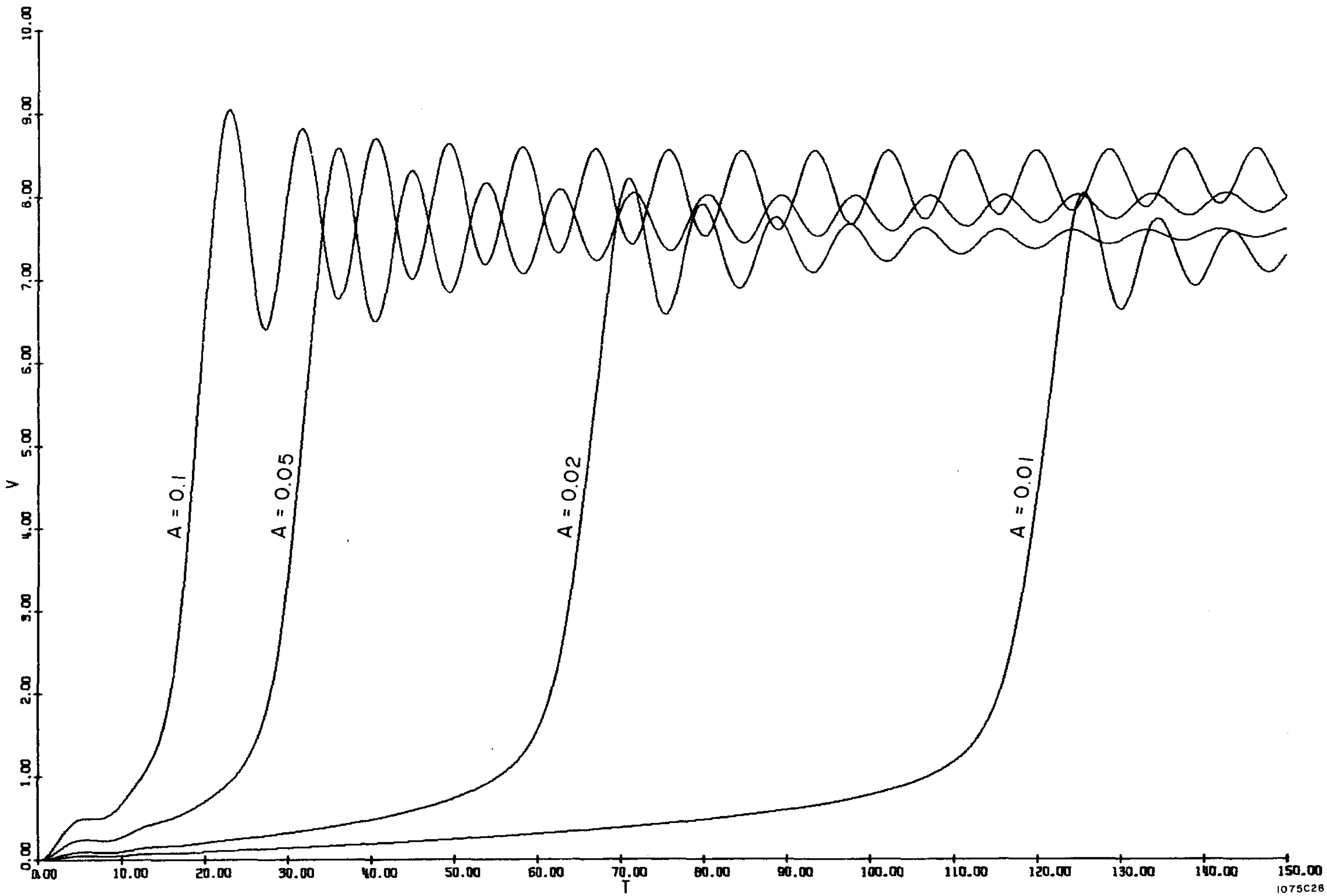

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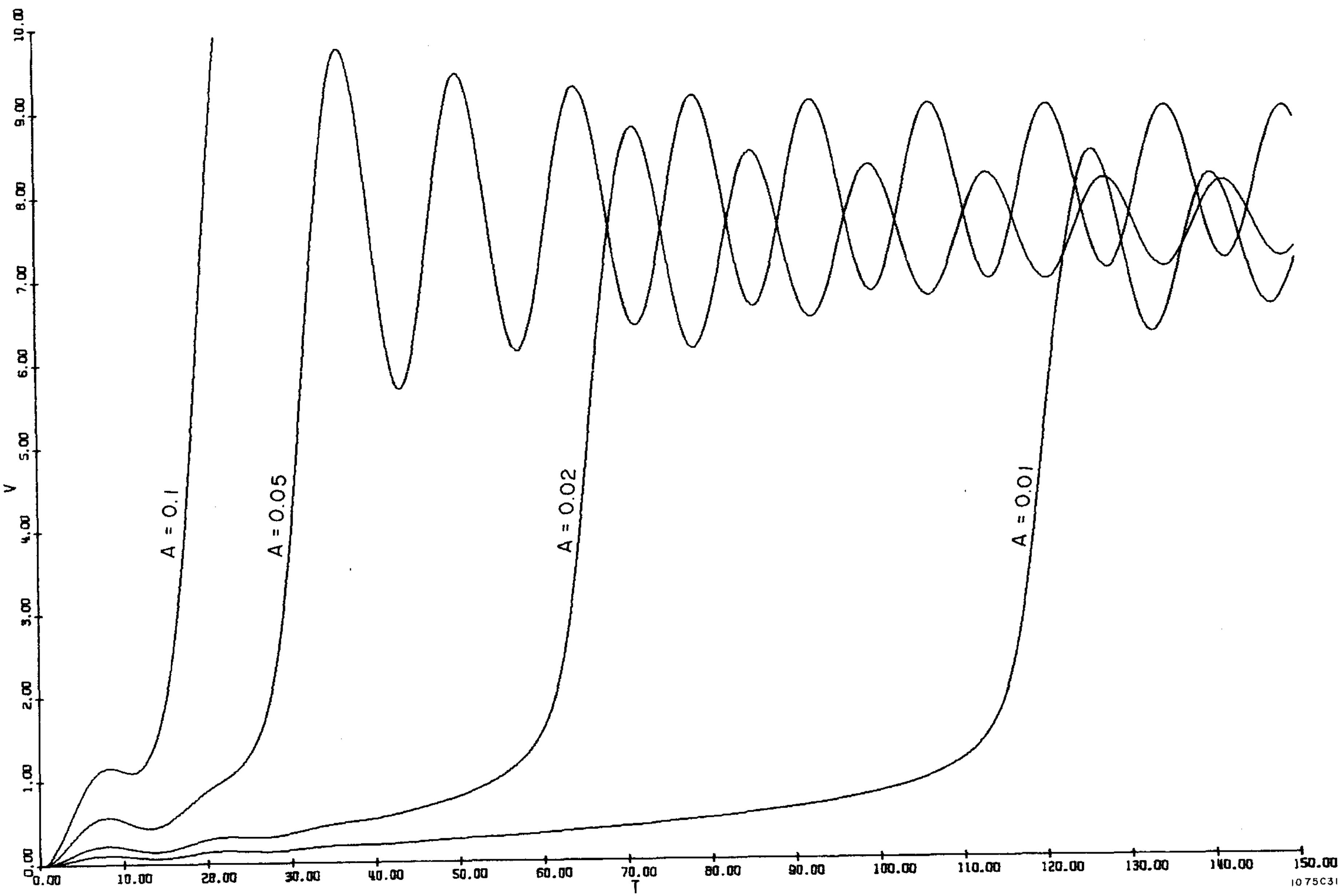

FIG. 8(f)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 0.5$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 5.0$.

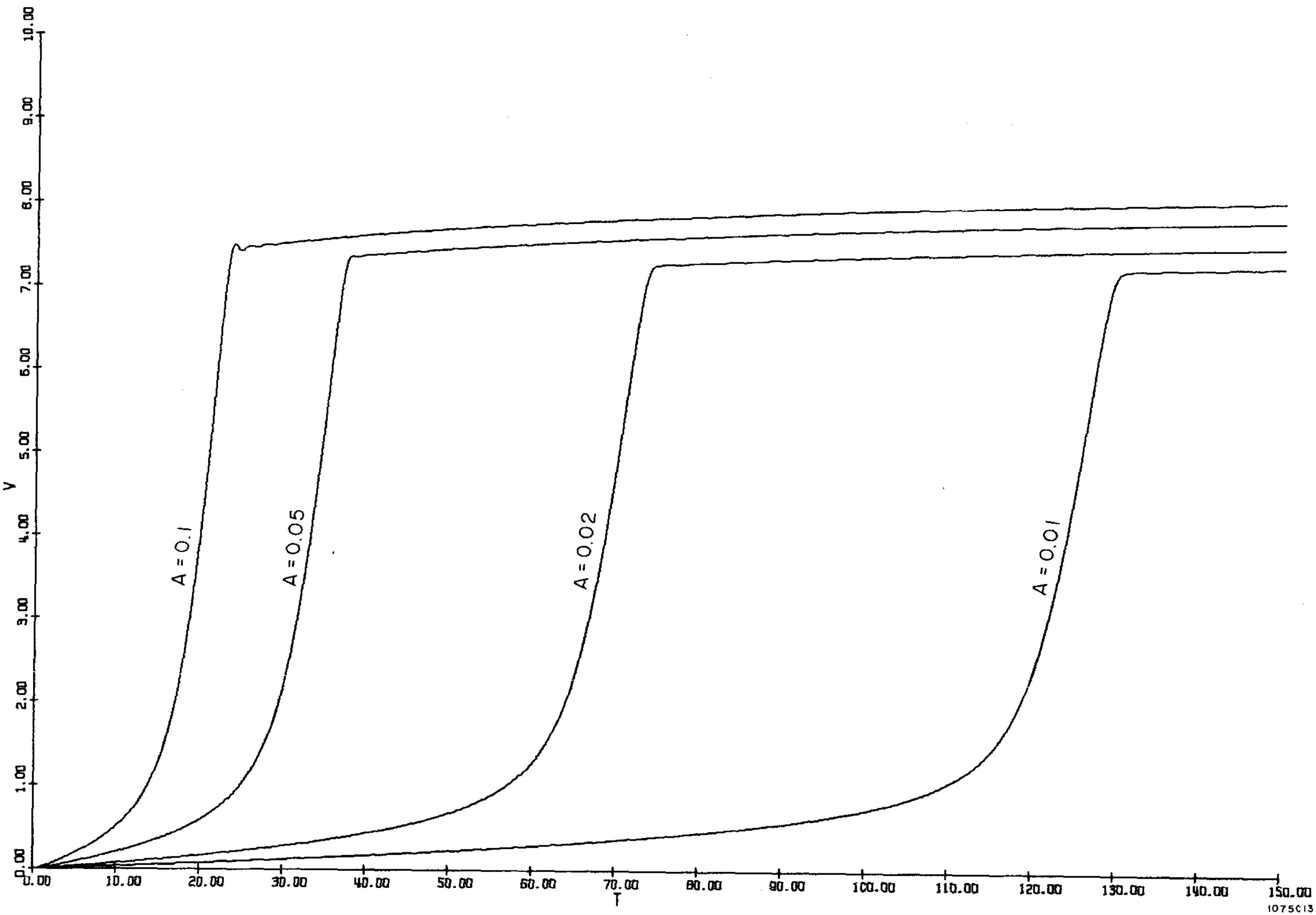

FIG. 9(a)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 1.0$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.1$.

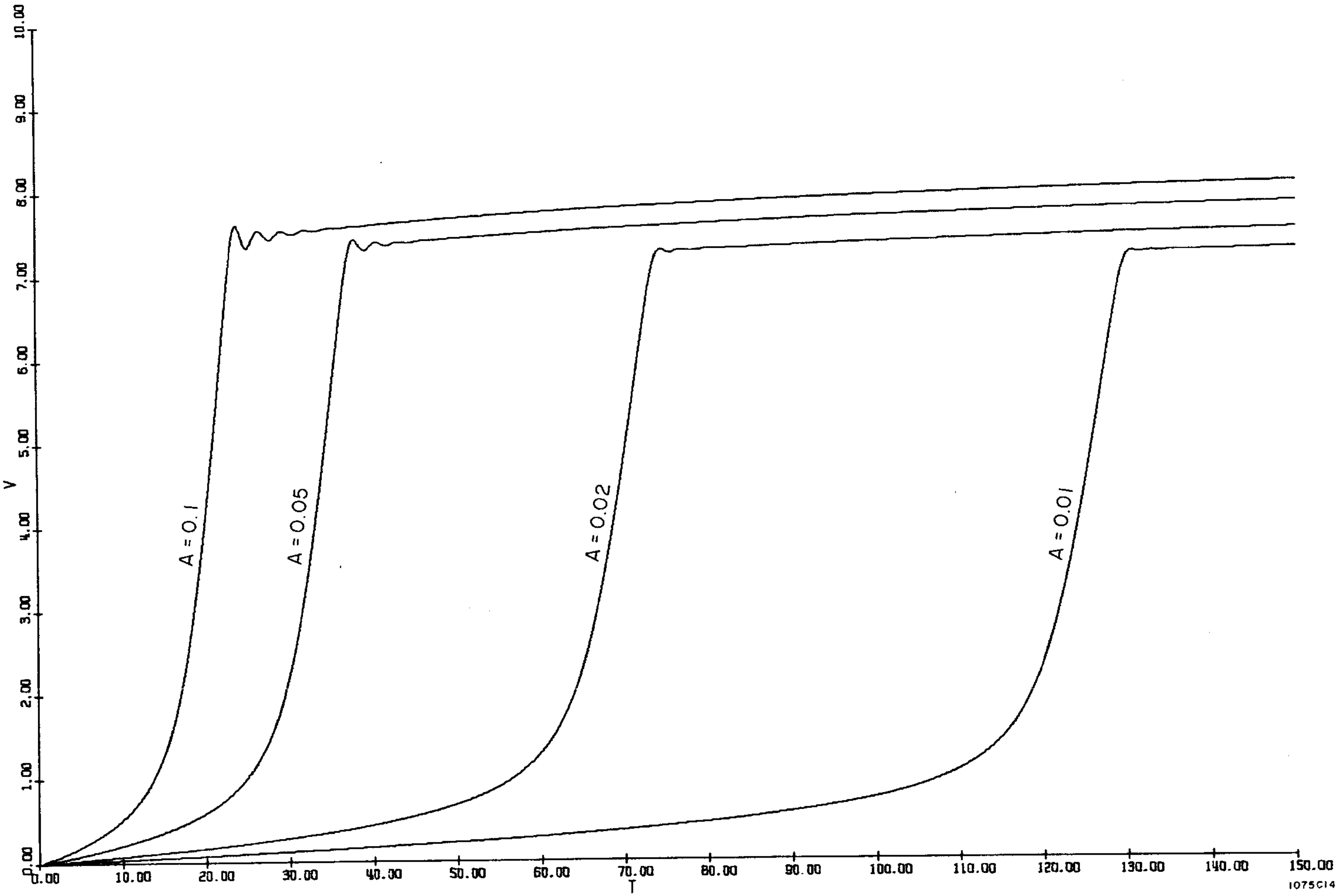

FIG. 9(b)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 1.0$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.2$.

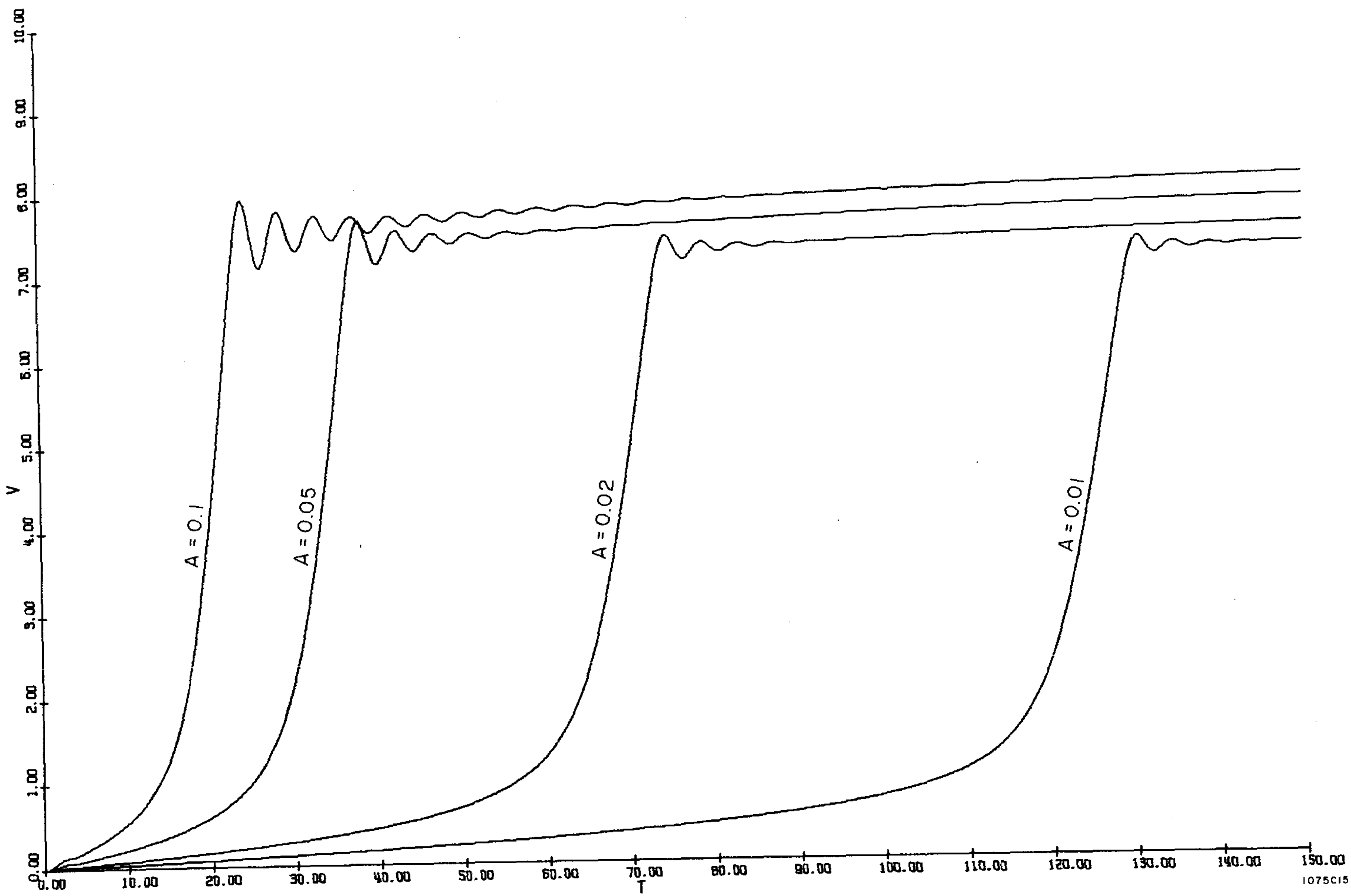

FIG. 9(c)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 1.0$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 0.5$.

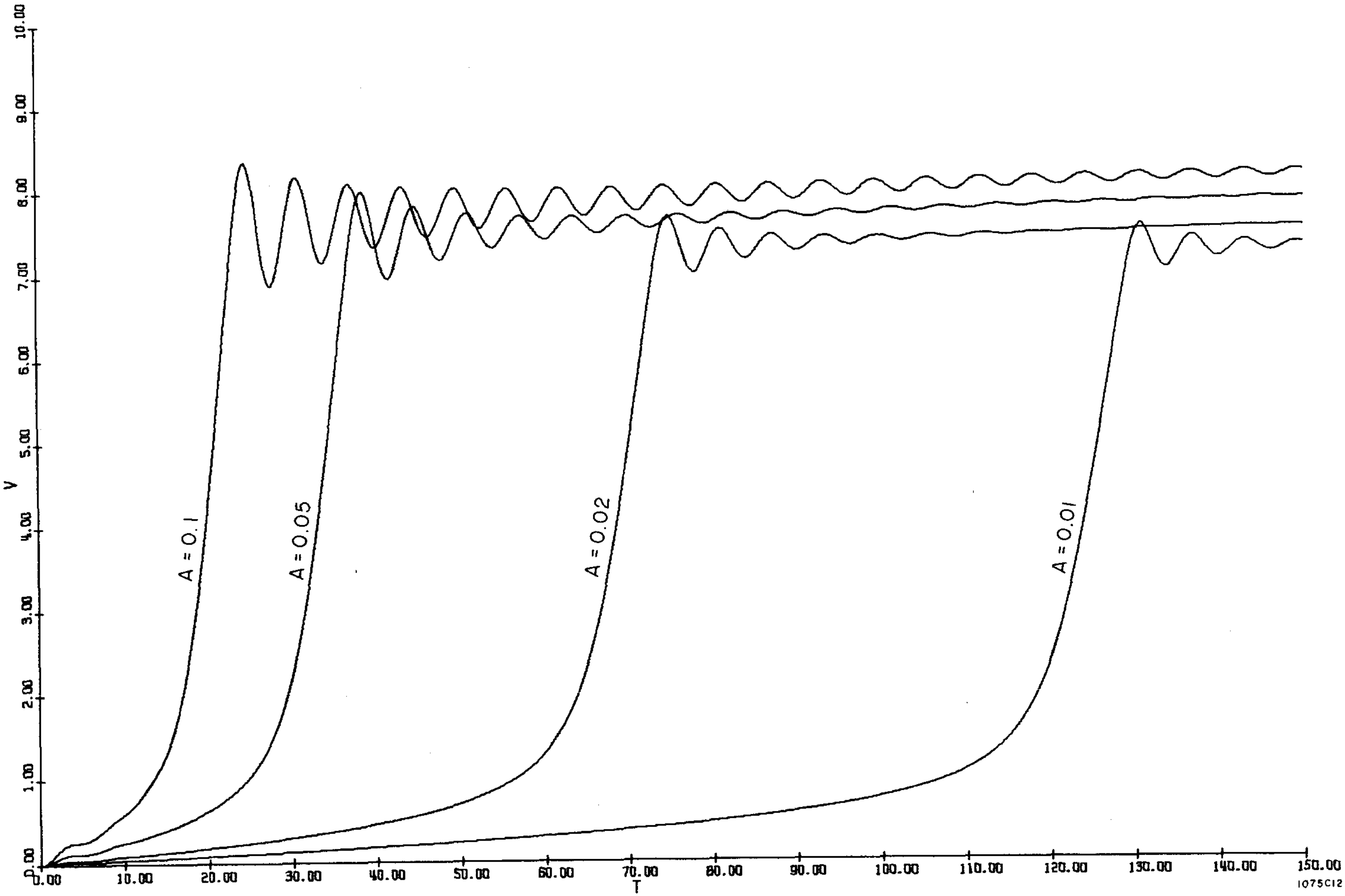

FIG. 9(d)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 1.0$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 1.0$.

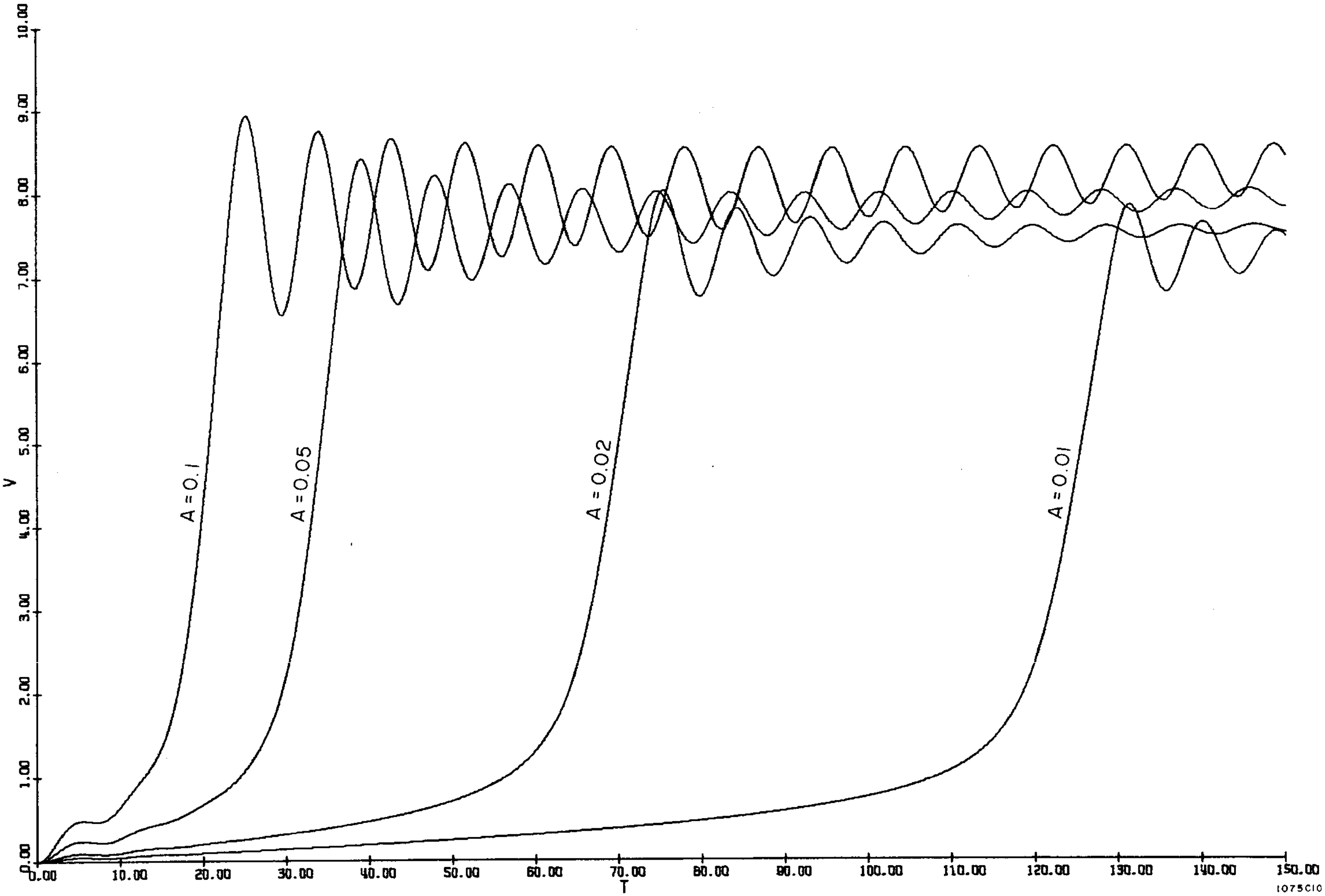

FIG. 9(e)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 1.0$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 2.0$.

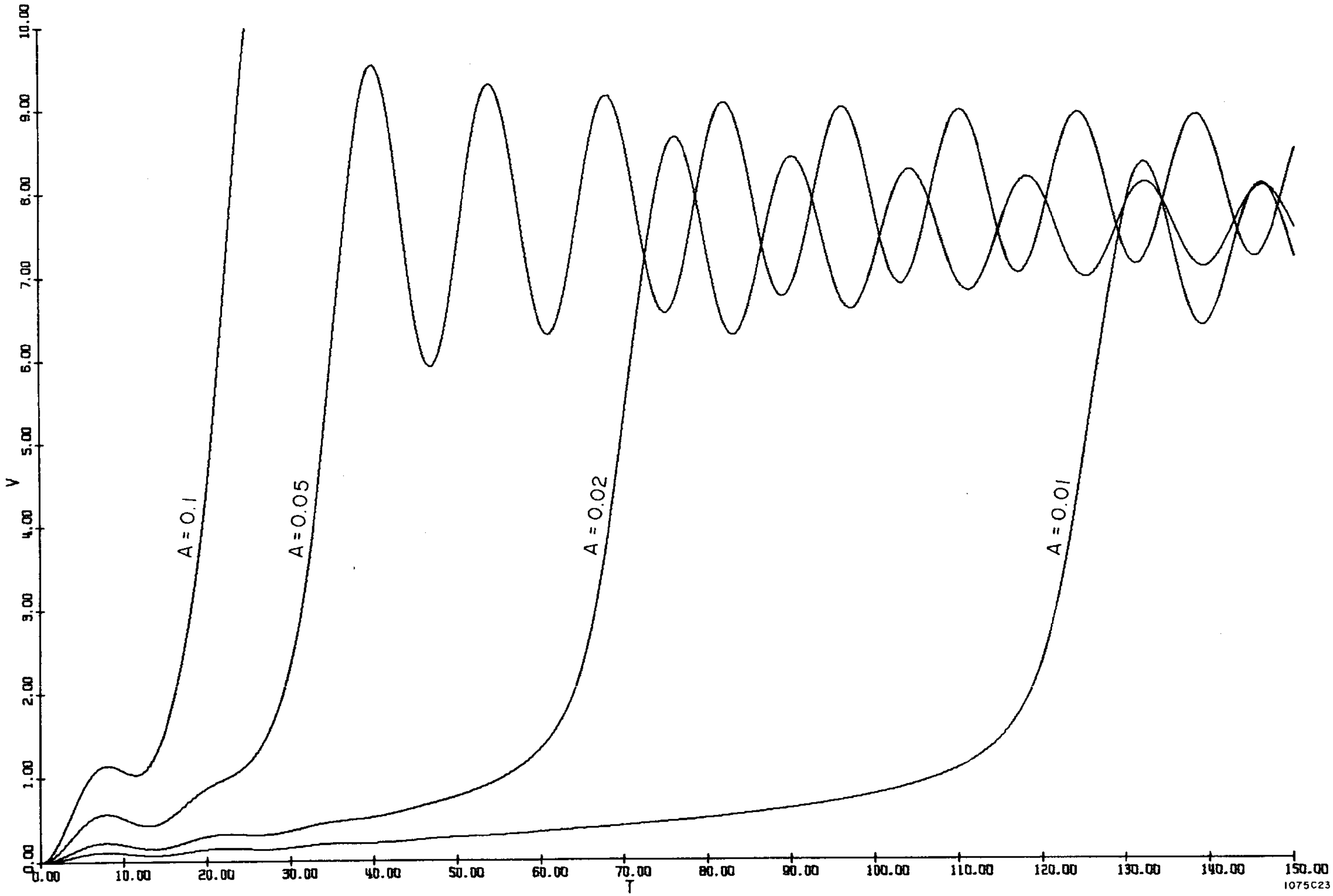

FIG. 9(f)--Normalized output voltage $V \equiv v_{out}/V_p$ as function of normalized time $T \equiv I_p t/(C_1 V_p)$ with the normalized drive current slope $A \equiv C_1 V_p k/I_p^2$ as parameter for $C_2/C_1 = 1.0$. Normalized inductance $L \equiv I_p^2 L_1 / \left(V_p^2 C_1\right) = 5.0$.

```
      FUNCTION F1(Y,B1,B2)
      B2Y=B2*Y
      IF(B2Y.GT.150.0)B2Y=150.0
      IF(Y.LT.-100.0)Y=-100.C
      F1=Y*EXP(1-Y)+1E-10*B1*EXP(B2Y)
      RETURN
      END


    1 FORMAT(6F10.4,I5,F10.4,I5)
    2 0FORMAT('1','A=',F10.4,5X,'L=',F10.4,5X,'DX=',F10.4,5X,'B1=',F10.4,
     15X,'B2=',F1C.4,5X,'C2=',F10.4)
    3 FORMAT('0',' ')
    4 0FORMAT(' ','X=',1PE9.2,' V2J=',1PE9.2,' V2JM1=',1PE9.2,' I2J=',
     11PE9.2,' I2JM1=',1PE9.2,'  RATE=',1PE9.2,' V1J=',1PE9.2,' V1JM1=',
     21PE9.2,' ID=',1PE9.2)
    5 0FORMAT('C','XMAX=',1PE10.3,' FMAX=',1PE10.3,' XMIN=',1PE10.3,
     1' FMIN=',1PE10.3)
      REAL A,L,DX,B1,B2,X,V1J,I2JM1,I2J,V2JM1,V2J,V1JM1,I2JM2,ID
      CALL STRTP1(10)
   10 READ(5,1)A,L,DX,B1,B2,C2,M,V2JST,IRET
   11 IF(A.LE.0)GC TO 100
      CALL PLOT1(0.0,0.0,3)
      IF(IRET.EQ.0)GO TO 12
      CALL PLOT1(25.0,0.0,-3)
      CALL AXIS1(C.C,0.0,'T',-1,15.0,C.0,0.0,10.,10.0)
      CALL PLOT1(0.0,0.0,3)
      CALL AXIS1(0.0,0.0,'V',+1,10.,90.0,0.0,1.0,10.0)
      CALL PLOT1(C.C,0.0,3)
   12 WRITE(6,2)A,L,DX,B1,B2,C2
      WRITE(6,3)
      ID=0
      RATE=0
   13 X=C
   14 V1J=0
   15 I2JM1=0
   16 I2J=0
   17 V2JM1=0
   18 V2J=0
   19 X=X+DX
   20 V1JM1=V1J
   21 V1J=V1JM1+(A*X-I2JM1)*DX
   22 IF(V2J.GT.10*DX)RATE=(V2J-V2JM1)/(V2J*DX)
   23 I2JM1=I2J
   24 I2J=I2JM1+(V1JM1-V2JM1)*DX/L
   25 V2JM1=V2J
   26 V2J=V2JM1+(I2J-ID)*DX/C2
   27 ID=F1(V2J,B1,B2)
   28 Z=FLOAT(M)
   29 IF(ABS(INT(X/DX+DX)/Z-INT((X/DX+DX)/Z)).GE.CX)GO TO 31
      XPLOT=0.1*X
      YPLCT=V1J
      IF(XPLCT.LE.0.0)XPLOT=0.0
      IF(XPLOT.GE.15.)GO TO 1C
      IF(YPLOT.LE.0.0)YPLCT=0.0
      IF(YPLOT.GE.10.)GO TO 10
      CALL PLOT1(XPLOT,YPLOT,2)
   31 CONTINUE
      GO TC 19
  100 CONTINUE
      CALL PLOT1(15.0,0.0,-23)
      CALL ENDP1
      STOP
      END
```

FIG. 10--Fortran-H computer program.