Hysteresis Turn-On-Off Voltages for a Neural-Type Cell*&

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Abstract

Bounds on the range of input voltages which lead to hysteresis in a neural-type cell are presented. These are important to the field of neural-type networks which operate on pulses, as do biological ones, since the presence of hysteresis allows for coding of the pulses.

I. Introduction

Pulse coded neural networks are under considerable study since they mimic the actual operation of biological neural networks. Basic to the operation of such neural networks is the neural-type cell [1], the essential processing element of this class of networks. One of the characteristics of the electronic neural-type cell we use [2] is its voltage-controlled hysteresis which allows for the coding and generation of the neural-type pulses. For such a circuit it is important to have a design theory for the coding of the pulses so that one can do information processing with pulse coded neural-type circuits. However, as yet the severely nonlinear nature of the circuit, involving a rather complicated hysteresis, has precluded an analytic development. Here, though we are able to give a low upper bound on the smallest input voltage needed to turn on the hysteresis as well as an upper lower bound on the largest input voltage needed to turn off the hysteresis.

II. The NTC

The CMOS circuit for the neural-type cell (NTC) under consideration here is shown in Fig. 1. For this circuit it can be seen that oscillations, as shown in Fig. 2, result at the output v_3 due to constant input voltages, v_1, whenever the i-v curve seen by the C-R_6 contains hysteresis and R_6 is appropriately chosen [3]. The appropriate choice for R_6 is such that the load line it determines passes through the two vertical sections of the hysteresis thus creating unstable resting states.

III. The Hysteresis Turn-On-Off Voltages

To obtain hysteresis in the circuit it is necessary to have both M_1 and M_2 pass through their ohmic regions when traversing the hysteresis curves since only then is there any possibility of control of the output due to the feedback transistor M_3. Beyond this it is also necessary that M_3 actually exerts the necessary control, which will only occur if its current can sufficiently modify the voltage across R_4 to allow M_2 to transition between its saturation and ohmic states. This requires that the drain current of M_3 is sufficient to bring its drain to source voltage low enough to put M_3 into the ohmic region but not sufficiently so as to cause it to lose control of the voltage on R_4.

Thus, as we raise v_1 from 0 we first find a value, call it v_{1low}, for which the desired hysteresis exists. As we raise it further we eventually reach a value, call it v_{1high}, at which the hysteresis disappears. The value for v_{1low} can be estimated by finding the smallest input voltage for which M_1 and M_2 simultaneously can be in their ohmic regions. If $V_{T1}>0$ and $V_{T2}<0$ are the respective threshold voltages of M_1 and M_2, then this requirement is

$$v_2 \leq v_1 - V_{T1} \qquad (1a)$$

$$v_4 - v_3 \leq v_4 - v_2 + V_{T2} \qquad (1b)$$

This latter constraint is

$$v_3 \geq v_2 - V_{T2} \qquad (1c)$$

Next we write KCL at the drain of M_1 using the assumption that M_1 and M_3 are operating in the ohmic region [4, p.51]

$$v_2 = V_{dd} - R_4\{\beta_1[2(v_1-V_{T1})v_2-v_2^2]+ \beta_3[2(v_3-V_{T3})v_2-v_2^2]\} \qquad (3)$$

Substituting (1a) & (1c) with their equality signs into (3) gives

$$R_4(\beta_1+\beta_3)(v_1-V_{T1})^2+ [1-2R_4\beta_3(V_{T2}+V_{T3})]\cdot(v_1-V_{T1})+ [V_{T1}-V_{dd}-R_4V_{T1}^2(\beta_1+\beta_3)-4R_4\beta_3V_{T1}V_{T3}]=0 \qquad (4)$$

Solving for v_1 gives, using $G_4=1/R_4$,

$$v_{1low} = V_{T1} + \{\beta_3(V_{T2}+V_{T3})-\tfrac{1}{2}G_4+\tfrac{1}{2}G_4\sqrt{\delta}\}/(\beta_1+\beta_3) \qquad (5a)$$

where

$$\delta=[1-2R_4(\beta_1+\beta_3)V_{T1}-2R_4\beta_3(V_{T2}+V_{T3})]^2-4R_4(\beta_1+\beta_3) \cdot[R_4(\beta_1+\beta_3)V_{T1}^2+2R_4\beta_3V_{T1}(V_{T2}+V_{T3})-V_{T1}-V_{dd}] \qquad (5b)$$

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For the upper value of the input voltage that gives hysteresis we note that control via M_3 on the voltage v_2 is lost when v_2 approaches zero. This latter occurs if the voltage across R_4 approaches V_{dd} and this will in turn happen when M_1 is in the saturation region and satisfies

$$V_{dd} = R_4\beta_1(v_1-V_{T1})^2 \qquad (6)$$

Solving for $v_1=v_{1high}$ we have

$$v_{1high} = V_{T1} + (G_4V_{dd}/\beta_1)^{1/2} \qquad (7)$$

The relations (5) and (7) give us an approximation of the range of the input v_1 for which oscillations are present in the output v_3. Two key assumptions that are implicit in the above results are that a) R_4 is not so big that M_1 loses control on v_2 near the high end of v_1 and b) R_4 is not so small that M_2 can never be turned on near the low end of v_1. On recognizing these assumptions we can obtain the approximate range of R_4 over which relations (5) and (7) are valid.

The calculation for the minimum value of R_4 proceeds as follows: For R_4 small, $V_{dd}-v_2$ is small so M_2 is cut off. Therefore:

$$I_2=0,\ v_4=V_{dd},\ v_3=0,\ v_2 \geq V_{dd} + V_{T2} \qquad (8)$$

As a consequence, M_3 is also cut off. Let us suppose that M_1 is ohmic, we have:

$$V_{dd}-R_4\beta_1[2(v_1-V_{T1})v_2-v_2^2] \geq V_{dd}+V_{T2} \qquad (9)$$

Now suppose $v_2 = V_{dd}+V_{T2}$ to simplify, replace in (9) taken as an equality, we get

$$v_1 = V_{T1}+\tfrac{1}{2}(V_{dd}+V_{T2})-V_{T2}/[2R_4\beta_1(V_{dd}+V_{T2})] \quad (10)$$

And we know from our simulations that M_1 is ohmic for small R_4 if $v_1 \geq v_{1high}$. Once again, taking the equality, we can combine (7) and (10) which leads to an equation of the second order in $x=1/R_4$:

$$V_{T2}{}^2x^2/[4\beta_1{}^2(V_{dd}+V_{T2})^2]-[(V_{dd}/\beta_1)+V_{T2}/2\beta_1]x+\tfrac{1}{4}(V_{dd}+V_{T2})^2 = 0 \qquad (11)$$

Equation (11) can be solved for x and therefore for R4. We get:

$$R_{4min} = V_{T2}{}^2/\beta_1(V_{dd}+V_{T2})^2[2V_{dd}+V_{T2}-2(V_{dd}(V_{dd}+V_{T2}))^{\frac{1}{2}}] \qquad (12)$$

The solution of (11) with the negative sign on the radical is chosen as the other solution has little physical meaning.

Proceeding toward the maximum value of R_4, we remark that for R_4 big, v_2 is small when $v_1=v_{1high}$. For these conditions, M_1 and M_3 are ohmic while M_2 is saturated. Neglecting I_3 with respect to I_1, we get

$$v_2 = V_{dd} - R_4\beta_1[2(v_1-V_{T1})v_2 - v_2{}^2] \qquad (13)$$

Which can be solved for v_1 (in order to equate it to v_{1high})

$$v_1 = V_{T1} + \tfrac{1}{2}v_2 + (V_{dd}-v_2)/2R_4\beta_1v_2 \qquad (14)$$

We then use (7) and (14) to obtain an equation in $x=1/R_4$:

$$(V_{dd}-v_2)^2x^2/(4\beta_1{}^2v_2{}^2)-(V_{dd}+v_2)x/(2\beta_1) + \tfrac{1}{4}v_2{}^2 = 0 \qquad (15)$$

which can be solved for x to finally give

$$R_{4max}=(V_{dd}-v_2)/\{\beta_1[V_{dd}+v_2-2(V_{dd}v_2)^{\frac{1}{2}}]v_2{}^2\} \qquad (16)$$

where the solution of (15) with a plus sign on the radical is taken as we want the maximum possible value on R_4. In evaluating (16) a nonzero value for v_2 is needed; since it is small it can be chosen near V_{T1}.

IV. Numerical Confirmation

Two cases were considered to check the above hysteresis turn on and off input voltages.

Case 1:

Using the values:
$V_{dd}=10V$, $\beta_1=5.5E-4$, $\beta_2=2.4E-4$, $\beta_3=5.5E-4$, $V_{T1}=V_{T3}=0.7V$, $V_{T2}=-0.9V$, R_4=2KOhms.

We find $v_{1low}=2.52V$ and $v_{1high}=3.7V$. These are to be compared with the SPICE simulation values of v_{1low} being about 2.6V and v_{1high} being about 3.6V.

For these values using equations (12) & (16), we get $R_{4mim}=840\Omega$, $R_{4max}=3.5k\Omega$ (v_2=1V being chosen), which is a good approximation of those, $R_{4min}=750\Omega$ and $R_{4max}=3.2k\Omega$, measured in PSPICE simulations.

Case 2:

Using the values:
$V_{dd}=5V$, $\beta_1=\beta_3=5.4E-5$, $\beta_2=2.5E-5$, $V_{T1}=V_{T3}=0.997V$, $V_{T2}=-0.8V$, R_4=20KOhms.

We find $v_{1low}=2.03V$ and $v_{1high}=3.14V$. These are to be compared with the SPICE simulation values of v_{1low} close to 2.2V and v_{1high} close to 3.5V.

V. Conclusions

In the above we have given the input voltages needed to guarantee the hysteresis necessary to make an NTC generate neural-type pulses. Because the voltages determined are based upon physical reasoning, they are only approximate but they do give reasonable bounds which check NTC simulations. It should be noted that hysteresis is guaranteed between the hysteresis v_{1low} and v_{1high} input voltages for suitable ranges of parameters. In the above we show the calculation to determine the range of R_4 while similar derivations can be performed to determine ranges of the β's.

Until now design equations have not been readily available for NTCs. Therefore we have formulated the equations for v_{1low} and v_{1high} in terms of circuit design parameters. With the voltages determined as above we are in a better position to make engineering designs of pulse coded neural-type networks.

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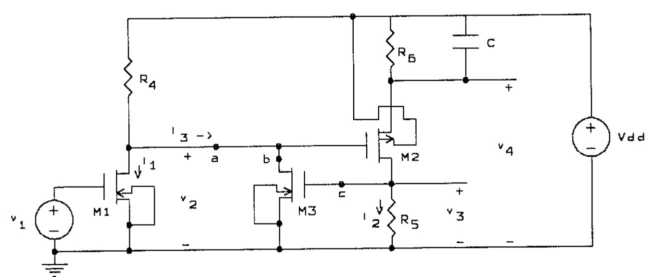

Figure 1. The Neural-Type Cell

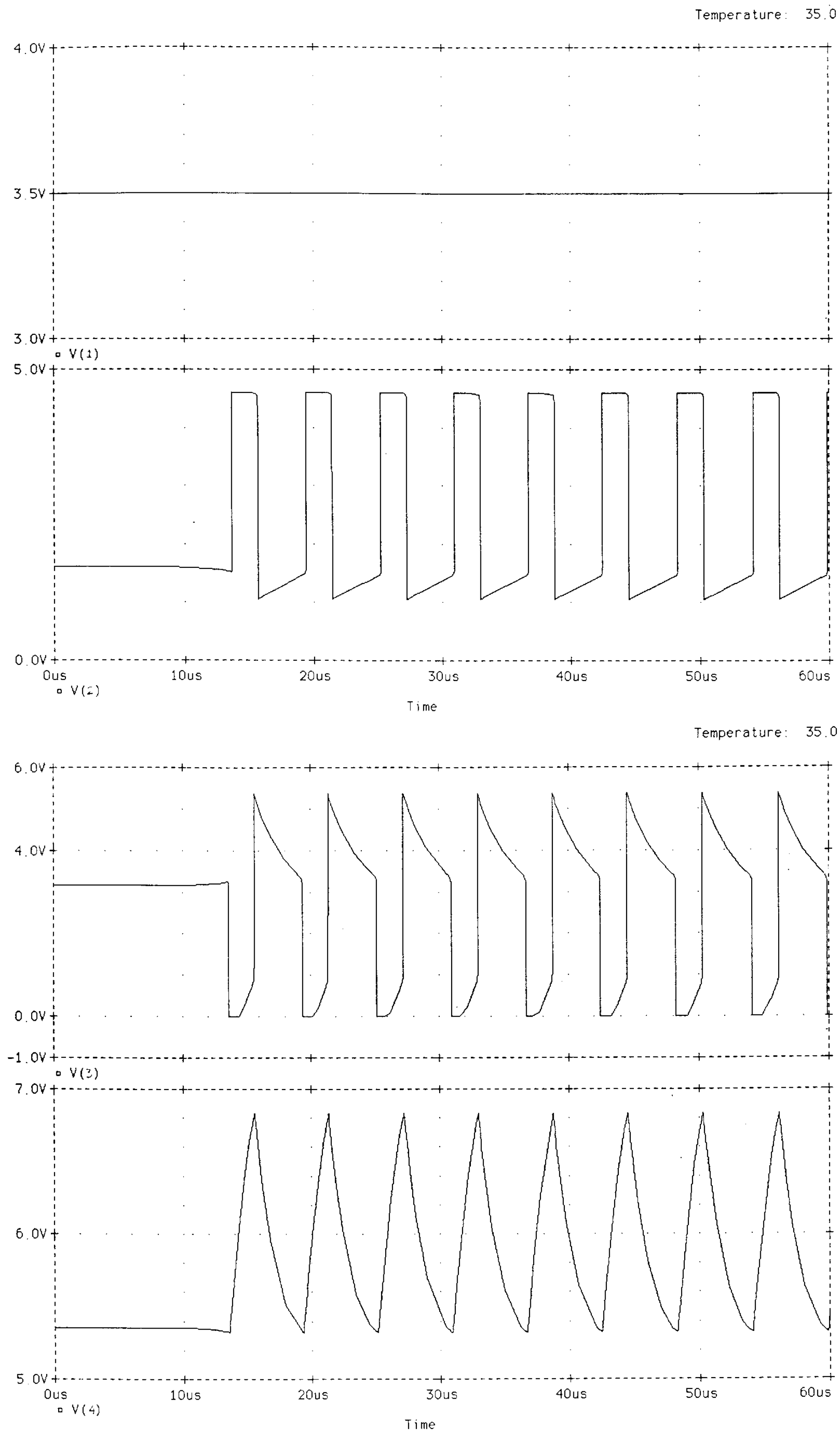

Figure 2. NTC Oscillations, v_1=3.5
v_1 = input, v_3 = output
v_2 and v_4 = internal signals