SOLID-STATE SWITCH MODELING

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DISCUSSION

The objective of this work is to predict voltages and currents of passive loads during turn-on and turn-off of remote power controllers (RPC'S). This report will be concerned with two devices built by Westinghouse for NASA, a five ampere device and a twenty ampere device. Both devices can be represented by the general model shown in Figure 1. When the RPC is turned on it will first act as a current source (position 1 of Figure 1) that supplies current to the passive load essentially independent of the elements of the load. This condition will hold until the switch saturates. The switch saturates when the load voltage reaches V_L^1 which is the applied voltage minus the saturated switch drop of about one half volt.

When the load voltage reaches V_L^1, S will switch to position 2 and the load voltage will remain at V_L^1. The load current will be determined by the load parameters and the conditions at switching. The steady state conditions will then be reached according to time constants determined by the load. However if the load current remains above a certain value (approximately 150 percent of rated current) for a period of time (approximately two seconds), a triping mechanism will disconnect the load.

When the RPC is turned off by the controller the load voltage will see an immediate small drop. This is represented in the model of Figure 1 as switching of S from position 2 to position 3. The load voltage will remain at a

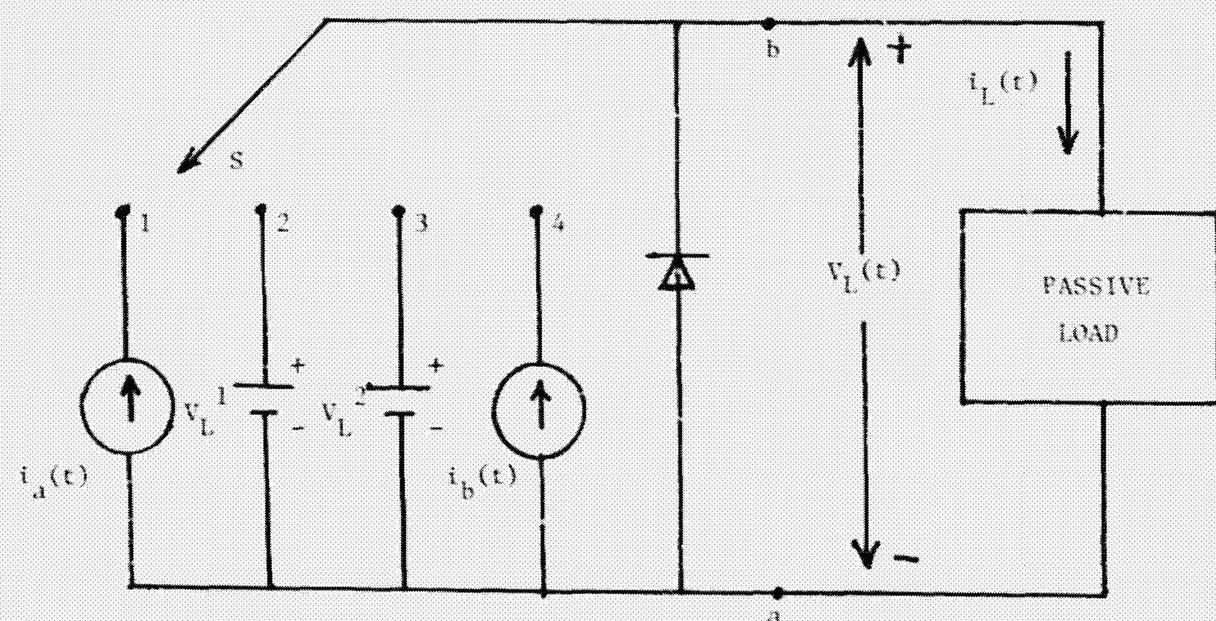


FIGURE 1

constant value $V_L^{\,2}$ for a time, t_s, which is a weak function of the value of load current at switching. After t_s the RPC will again act as a current source. This is represented in Figure 1 with S switching from position 3 to position 4.

The model of Figure 1 contains a diode across the load. Usually this diode is reverse biased and can be ignored. However for certain inductive loads it is possible for the load voltage to go negative. When the load voltage goes negative the diode starts to conduct and the load current is no longer equal i_b of Figure 1. This conduction has been considered in analyzing turn-off of inductive loads. The model will now be used to analyze the turn-on and turn-off of certain loads. Experimental results will be given for comparison. However, the equations of the current and voltages of Figure 1 will first be given. They are:

$$i_a(t) = \frac{I_1}{T_1}\left[t\,U(t) - (t - T_1)\,U(t - T_1)\right] + I_2\left[1 - e^{-\alpha(t - T_1)}\right]U(t - T_1) \tag{1}$$

$$V_L^{\,1} = V_a - V_{ss}^{\,1} = V_a - 0.5 \text{ Volts} \tag{2}$$

$$V_L^{\,2} = V_a - V_{ss}^{\,2} = V_a - 1.5 \text{ Volts} \tag{3}$$

and

$$i_b(t) = I_3\, e^{-\frac{t - t_s}{\tau}}\, U(t - t_s) \tag{4}$$

R-C Load

The circuit of Figure 2 will be used to analyze a general R-C load. When the RPC is first turned on $i_L(t)$ will equal $i_a(t)$ of Equation 1. Of course $i_L = i_1 + i_2$. The load voltage will be given by

$$V_L = \frac{I_1 R_2}{T_1}\left[\{t - R_2C(1 - e^{-\beta t})\}\,U(t) - \{t - T_1 - R_2C(1 - e^{-\beta(t - T_1)})\}\,U(t - T_1)\right]$$
$$+ R_2 I_2\left[1 + \frac{1}{1 - \alpha/\beta}\{\alpha C R_2\, e^{-\beta(t - T_1)} - (1 - \alpha C R_1)\, e^{-\alpha(t - T_1)}\}\right]U(t - T_1) \tag{5}$$

where $\beta = \frac{1}{C(R_1 + R_2)}$.

The time, T_2, that S switches from position 1 to position 2 is found by the relation

$$V_L(T_2) = V_L^{\,1} \tag{6}$$

After T_2 the voltage, V_L, across the load remains at $V_L^{\,1}$ and the current is given by

$$i_L(t) = \left[\frac{V_L^{\,1}}{R_2} + \left(\frac{V_L^{\,1} - V_C(T_2)}{R_1}\right) e^{-\frac{(t - T_2)}{R_1 C}}\right] U(t - T_2) \tag{7}$$

where $V_C(T_2)$ is the capacitor voltage at T_2 and is given by

$$V_C(T_2) = (I_1 + I_2)\, R_2 + \frac{I_1 R_2 C(R_1 + R_2)}{T_1} \left(e^{-\beta T_2} - e^{-\beta(T_2 - T_1)}\right)$$

$$+ \frac{1}{1 - \alpha/\beta} \left\{\alpha C I_2 R_2 (R_1 + R_2)\, e^{-\beta(T_2 - T_1)} - e^{-\alpha(T_2 - T_1)}\right\} \tag{8}$$

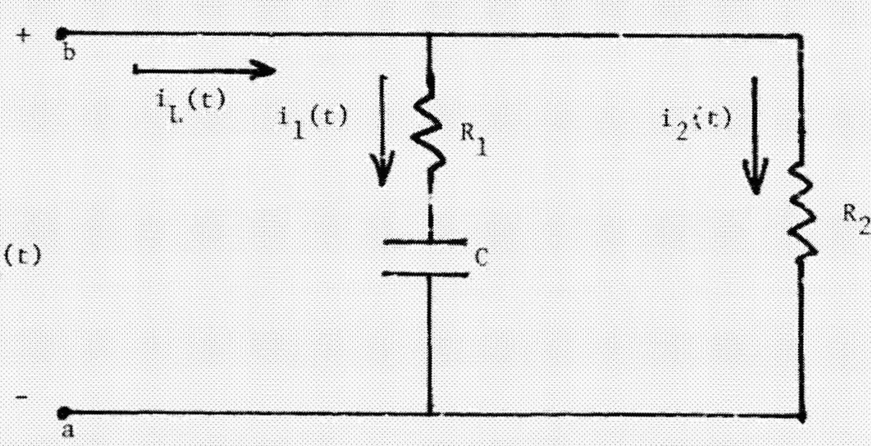


FIGURE 2

For the turn-off assume that a steady state is reached and the RPC is turned off at $t = 0$. S is then moved from position 2 to position 3. At switching the voltage across the capacitor will be equal to $V_L^1 > V_L^2$ and hence, $i_1(t)$ will at first be negative and the total load current $i_L(t)$ will be less than V_L^2/R_2. The total load current for the range $0 \leq t \leq t_s$ will be given by

$$i_L(t) = \frac{V_L^2}{R_2} - \left(\frac{V_L^1 - V_L^2}{R_1}\right)e^{-t/R_1C} \tag{9}$$

This equation holds until $t = t_s$. Then

$$i_L(t_s) = \frac{V_L^2}{R_2} - \left(\frac{V_L^1 - V_L^2}{R_1}\right) e^{-t_s/R_1C} \doteq I_3 \tag{10}$$

At $t = t_s$ the S switches from position 3 to position 4, and

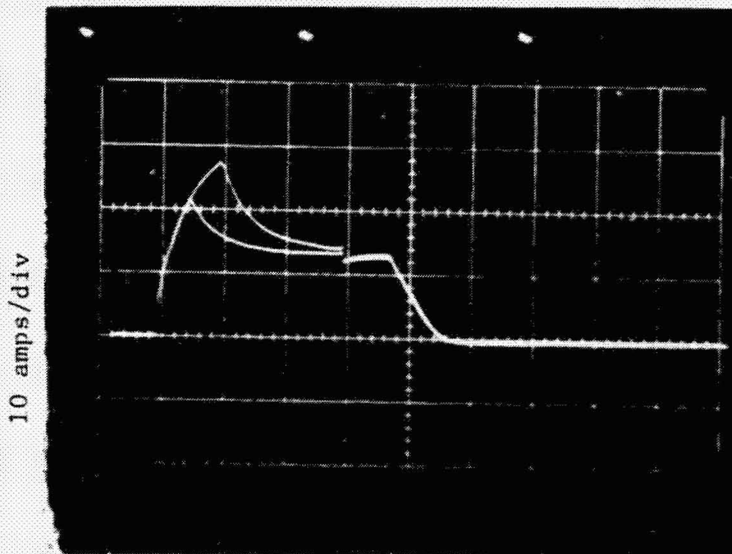
$$i_L(t) = I_3\, e^{-(t - t_s)/\tau}\, U(t - t_s) \tag{11}$$

The load voltage is given by

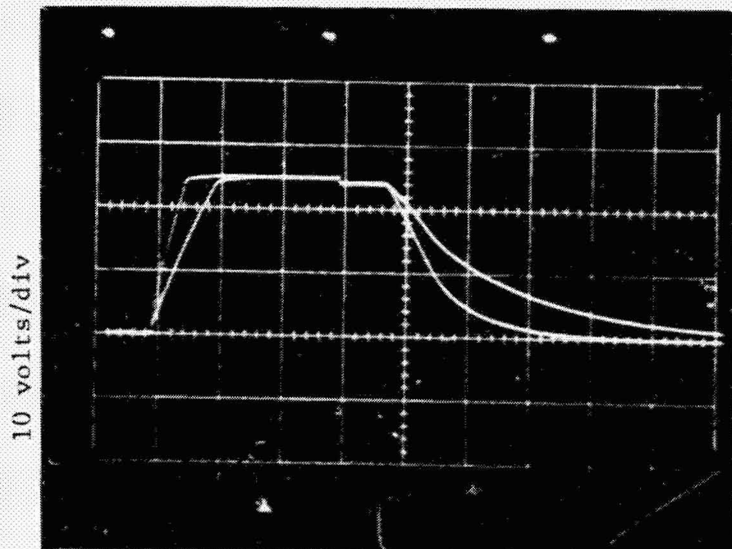
$$V_L(t) = \Big[\frac{R_2I_3}{C(R_1 + R_2) - \tau} \{(R_1C - \tau)\, \epsilon^{-(t - t_s)/\tau} + \frac{2R_2}{R_1 + R_2}\, e^{-\beta(t - t_s)}\}$$

$$+ \frac{R_2V_C(T_3)}{R_1 + R_2}\, e^{-\beta(t - t_s)}\Big]\, U(t - t_s) \tag{12}$$

Figure 3 shows the turn-on and turn-off characteristics of the R-C load of Figure 2. Traces of the load current versus time are given in Figure 3(a) for two different values of capacitance. The corresponding traces of load voltage versus time are given in 3(b).



(a)



(b)

FIGURE 3

R-L Load

The R-L load is analyzed the same as the R-C load. For the notation refer to Figure 4. For turn-on, the load current is given by equation (1) for load voltages less than $V_L^{\,1}$. The corresponding load voltage is given by

$$V_L(t) = \frac{I_1}{T_1}\left[\left\{\frac{R_2^{\,2}}{\beta(R_1 + R_2)}(1 - e^{-\beta t}) + \frac{R_1R_2}{R_1 + R_2}t\right\}U(t) - \left\{\frac{R_2^{\,2}}{\beta(R_1 + R_2)}\right.\right.$$

$$\left.\left.\times\,(1 - e^{-\beta(t - T_1)}) + \frac{R_1R_2}{R_1 + R_2}(t - T_1)\right\}U(t - T_1)\right]$$

$$+ I_2\left[\frac{R_1R_2}{R_1 + R_2} - \frac{\alpha R_2^{\,2}}{(R_1 + R_2)(\beta - \alpha)}e^{-\beta(t - T_1)}\right.$$

$$\left. - \frac{1\,R_2(R_1 - \alpha L)}{L(\beta - \alpha)}e^{-\alpha(t - T_1)}\right]U(t - T_1) \tag{13}$$

where $\beta = \dfrac{R_1 + R_2}{L}$.

Equation (13) is monitored to determine the time T_2 that $V_L(t) = V_L^{\,1}$. The load voltage will remain at $V_L^{\,1}$ for $t > T_2$. To determine $i_L(t)$ for $t > T_2$ the value $I_o = i_1(T_2) = i_L(T_2) - V_L^{\,1}/R_2$ is first found. It is given by

$$I_o = i_1(T_2) = \frac{I_1}{T_1}\left[\left\{\frac{R_2}{R_1 + R_2}T_2 - \frac{R_2}{\beta(R_1 + R_2)}(1 - e^{-\beta T_2})\right\}\right.$$

$$\left. + \left\{\frac{R_2}{\beta(R_1 + R_2)}(1 - e^{-\beta(T_2 - T_1)}) - \frac{R_2}{R_1 + R_2}(T_2 - T_1)\right\}\right]$$

$$+ I_2\left[\frac{R_2}{R_1 + R_2} - \frac{L\beta - R_1}{L(\beta - \alpha)}e^{-\alpha(T_2 - T_1)} + \frac{\alpha R_2\,e^{-\beta(T_2 - T_1)}}{(R_1 + R_2)(\beta - \alpha)}\right. \tag{14}$$

Then the load current is

$$i_L(t) = \left\{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)V_L^{\,1} + \left(I_o - \frac{V_L^{\,1}}{R_1}\right)e^{-\frac{R_1}{L}(t - T_2)}\right\}U(t - T_2) \tag{15}$$

For the turn-off the load voltage will again be $V_L^{\,2}$ for $t < t_s$ and the load current for this time will be

$$i_L(t) = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) V_L^{\,2} + \left[\frac{V_L^{\,1} - V_L^{\,2}}{R_1}\right] e^{-\frac{R_1}{L} t} \tag{16}$$

At $t = t_s$ the switch comes out of saturation and the load current is given by Equation (4). To find the value of $i_1(t_s)$, the value of current through the inductor at switching is monitored. It is given by

$$I^o = i_1(t_s) = i_L(t_s) - \frac{V_L^{\,2}}{R_2} \tag{17}$$

The load voltage is then given by

$$V_L(t) = \frac{I_3}{\tau(R_1 + R_2) - L} \{(\tau R_1 - L)\, e^{-(t - t_s)/\tau} + \tau R_2^{\,2} e^{-\beta(t - t_s)}\}\, U(t - t_s)$$

$$- R_2 I_o^{\,o}(T_3)\, e^{-\beta(t - t_3)} U(t - t_s) \tag{18}$$

The above analysis is complete except for certain R-L loads that will drive the load voltage negative. If the load voltage goes more negative than the built-in voltage of the diode (few tenths of a volt) the diode will start to conduct and must be included in the analysis. For this analysis assume

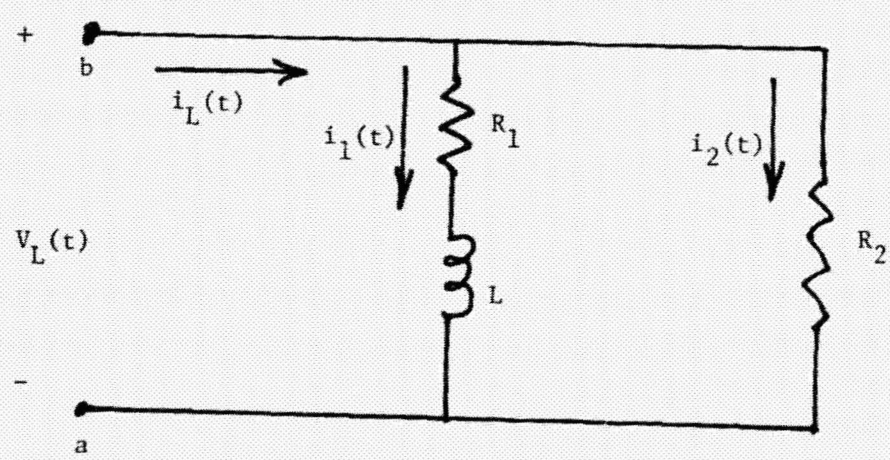


FIGURE 4

$V_L(t) = -V_{bi}$ at $t = T_4$. The value of T_4 can be determined from equation (18). Again the value of current through the inductor at T_4 must be determined. This value is given by

$$I_o^{\,o} = i_1(T_4) = i_L(T_4) + \frac{V_{bi}}{R_2} \tag{19}$$

Assuming that the diode can be modeled with a resistance γ_d the load voltage and current for $t > T_4$ are given by

$$V_L(t) = \frac{I_3 R_2}{\tau(R_2 + R_1) - L}\{(\tau R_1 - L)\, e^{-(t - t_s)/\tau} + \tau R_2\, e^{-\beta(t - t_s)}\}\, U(t - t_s)$$

$$- R_2 I_o^{\,o}(T_4)\, e^{-\beta(t - T_4)}\, U(t - T_4) \tag{20}$$

and

$$i_L(t) = \frac{R_2 I_o^{\,o}(T_4)}{\gamma_d}\, e^{-\beta(t - T_4)}\, U(t - T_4) + I_3[1 - \frac{R_2(\tau R_1 - L)}{\gamma_d\,\{\tau(R + R_1) - L\}}]$$

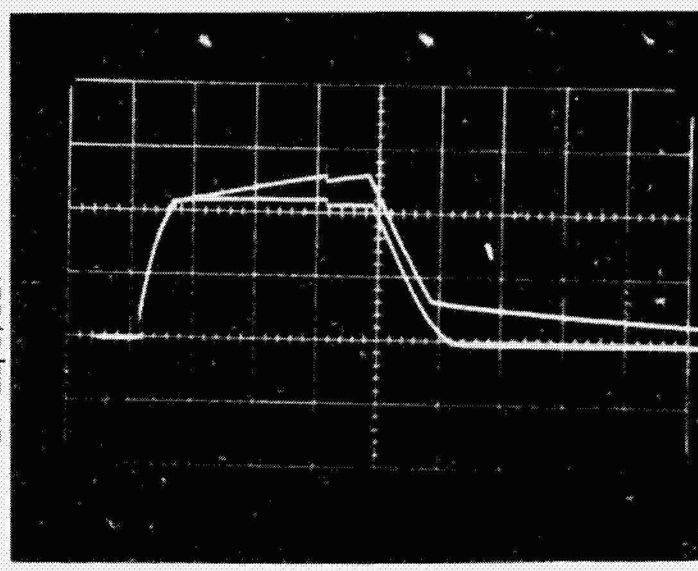
$$e^{-(t - t_s)/\tau}\, U(t - T_3) - \frac{I_3 \tau R_2^{\,2}}{\gamma_d\{\tau(R + R_1) - L\}}\, e^{-\beta(t - t_s)}\, U(t - T_s) \tag{21}$$

Figure 5 shows the turn-on and turn-off characteristics for a R-L load. Figure 5(a) is traces of the load currents versus time for two different values of R_1 and L. Figure 5(b) shows the corresponding traces of load voltage versus time. In each case the load configuration of Figure 4 was used.

All the experimental results were obtained using the Westinghouse twenty ampere RPC. Two Sears Die Hard batteries were connected in series and used as the power supply. The control signal was from a Hewlett Packard 214 pulser with a pulse rate low enough so that all transients in the RPC and the load would completely vanish before the next pulse.

The parameters for Equations (1) and (4) were obtained by using pure resistive loads and fitting experimental results to the equations. The values were found to be: $T_1 = 0.1$ m sec, $I_1 = 3.5$ amps, $I_2 = 27.3$ amps, $\alpha = 0.9$ /m sec, $t_s = t_o - K_1 I_3$ (where $t_o = 1.86$ m sec and $K_1 = 0.027$m sec/amp) and $\tau = \tau_o + K_2 I_3$ (where $\tau_o = 0.39$ m sec and $K_2 = 0.076$ m sec/amp).

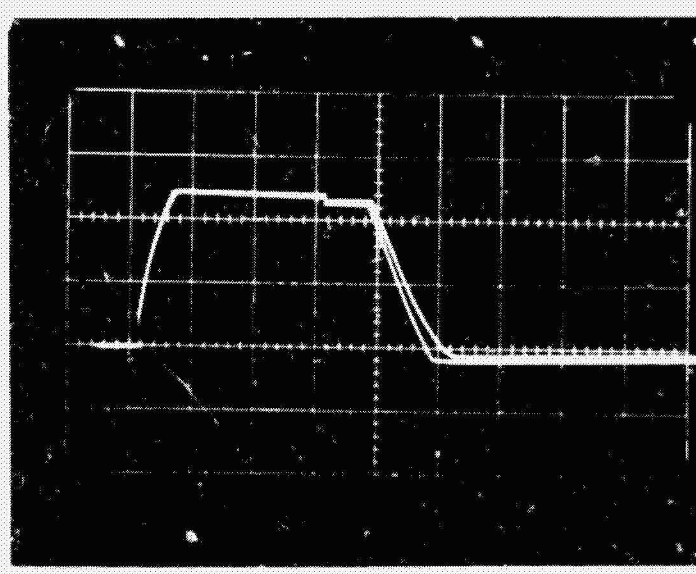
10 amps/div



2 m sec/div

(a)

10 volts/div



2 m sec/div

(b)

FIGURE 5