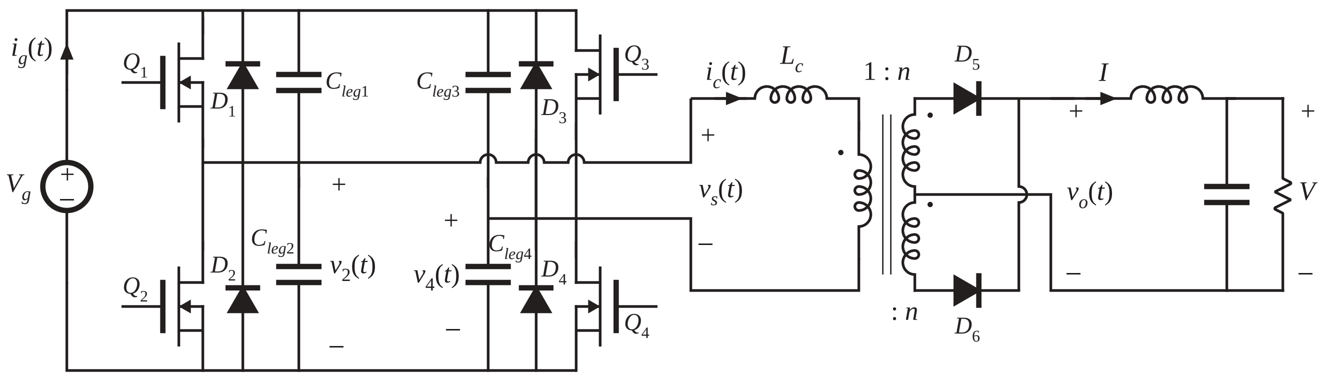
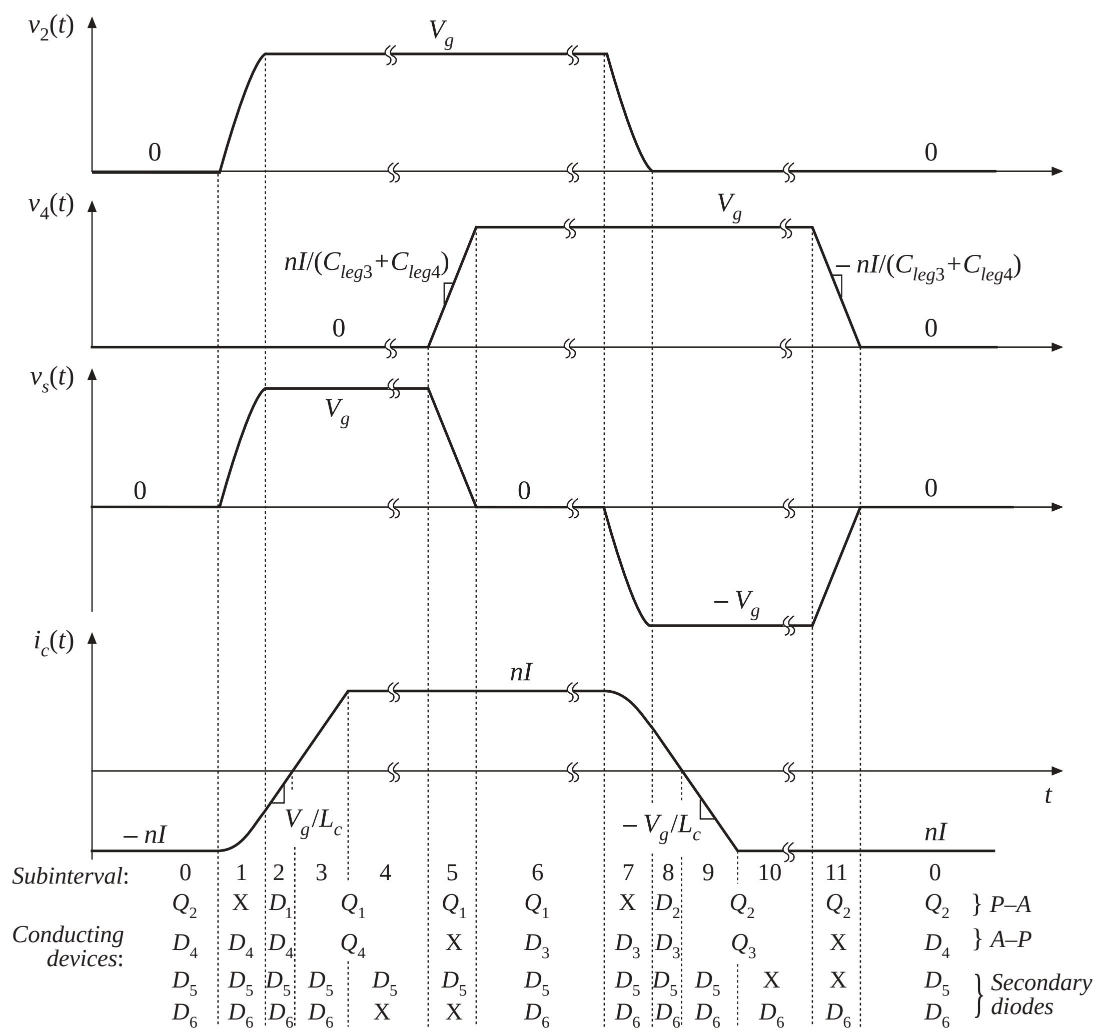
State Plane Analysis of Basic Zero-Voltage Transition (ZVT) Full-Bridge Converter

Schematic and waveforms:





Subinterval 1

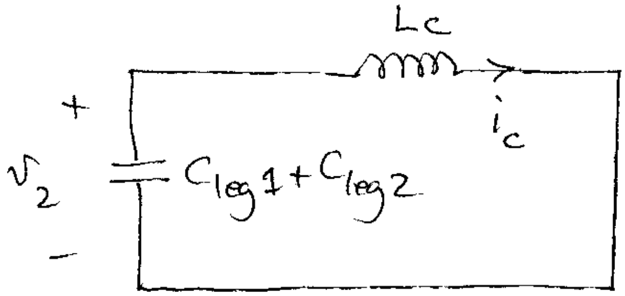
Begins when Q_2 turns off

D_4, D_5, D_6 conduct

Note that when D_5 and D_6 both conduct, then the transformer secondary is short-circuited.

$i_c < 0$. Initial $v_2 = 0$, $i_c = -nI$

Circuit becomes



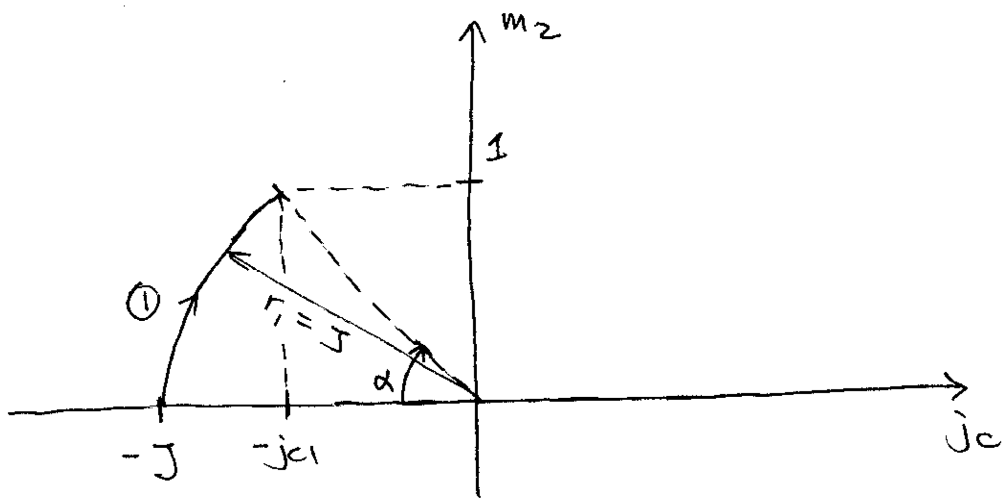
Normalized state plane: Define $V_{base} = V_g$,

$$I_{base} = \frac{V_g}{R_0}, \quad R_0 = \sqrt{\frac{L_c}{C_{leg1} + C_{leg2}}}$$

$$\omega_0 = \frac{1}{\sqrt{L_c\left(C_{leg1} + C_{leg2}\right)}}$$

$$j_c = \frac{i_c}{I_{base}}, \quad J = \frac{nI}{I_{base}}, \quad m_2 = \frac{v_2}{V_{base}}$$

initial $j_c = -J$, $m_2 = 0$



State plane trajectory follows circular arc centered at origin. Radius $r_1 = J$,

Interval ends when $v_2 = V_g$, forward-biasing D_1.

At end of interval, $m_2 = 1$ and $j_c = -j_{c1}$

Solution of state plane geometry:

$$j_{c1} = \sqrt{r_1^2 - 1} = \sqrt{J^2 - 1}$$

and $\alpha = \omega_0 t_1 = \tan^{-1}\left(\frac{1}{+j_{c1}}\right) = \tan^{-1}\left(\frac{1}{\sqrt{J^2-1}}\right)$

where interval 1 length $= t_1$.

For zero-voltage switching, we require $J \geq 1$.

If $J < 1$, then v_2 never reaches V_g, and switching loss occurs when Q_1 turns on.

Subinterval 2 $\quad D_1$ is forward-biased

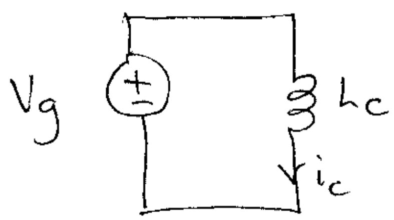
Subinterval 3 $\quad$ conducting devices: D_1, D_4, D_5, D_6

or $\quad Q_1, Q_4, D_5, D_6$

initial $i_c = -i_{c1}$

let $t_3 + t_2$ = length of intervals 2 and 3

Circuit is

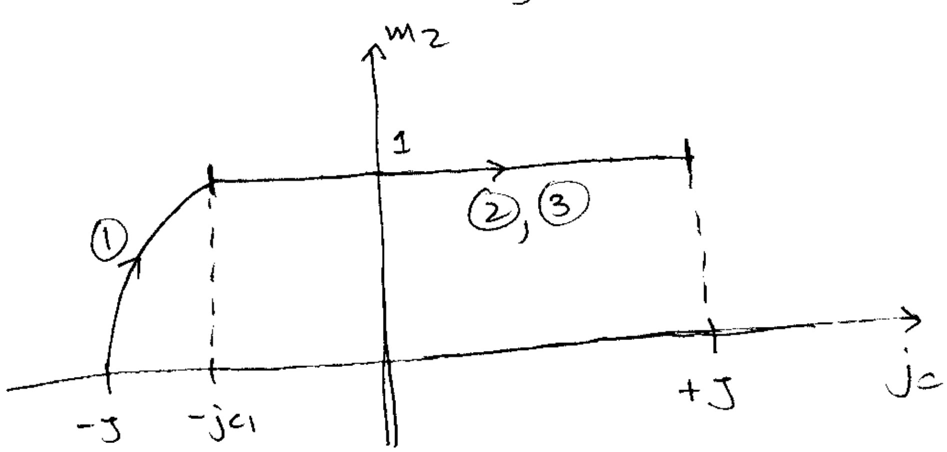


i_c increases with slope $\frac{V_g}{L_c}$

Interval end when $i_c = nI$; D_6 then becomes reverse-biased

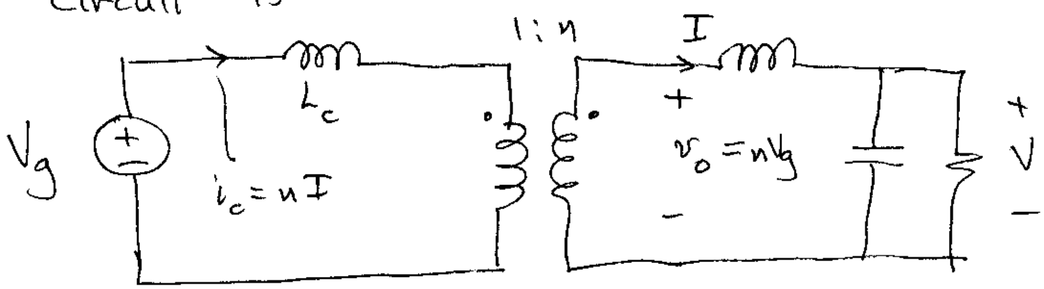
so $\frac{V_g}{L_c}(t_2 + t_3) = nI + i_{c1}$

$\Rightarrow t_3 + t_2 = (nI + i_{c1}) \frac{L_c}{V_g}$



Subinterval (4) D_6 is reverse-biased.
Q_1, Q_4, D_5 conduct

Circuit is



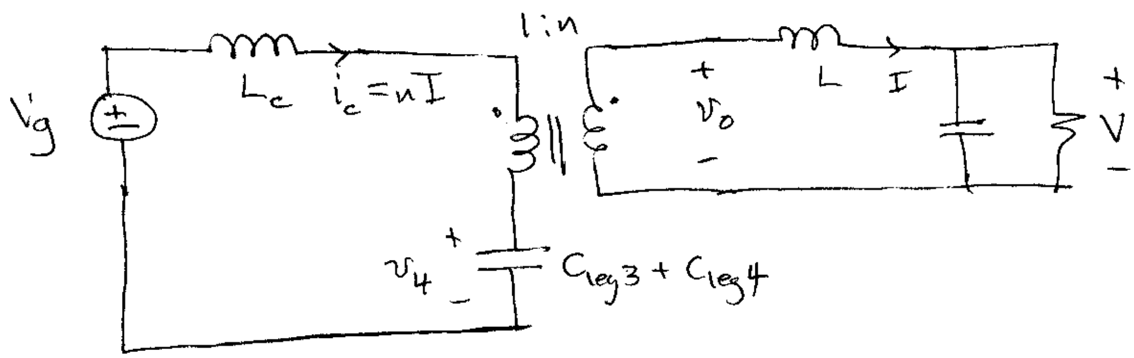
Power is transferred through switches and transformer to output.

$i_c = nI$ constant

$v_2 = V_g$ constant

Interval ends when controller turns off Q_4.

Subinterval (5) Q_4 is off. Q_1, D_5 conduct



v_4 charges from 0 to V_g, with slope $\dfrac{nI}{C_{leg3} + C_{leg4}}$

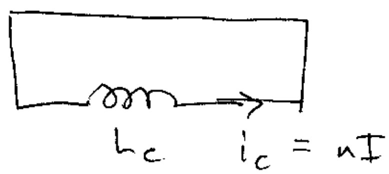
Length of interval is $t_5 = \dfrac{V_g}{nI}(C_{leg3} + C_{leg4})$

During this interval, voltage across L_c is $L_c \dfrac{d(nI)}{dt} \approx 0$
and $v_o = n(V_g - v_4)$

Subinterval 6

Q_1, D_3, D_5, D_6 conduct.
interval begins when D_3 and D_6 are forward-biased.

Circuit is



i_c remains constant and equal to nI

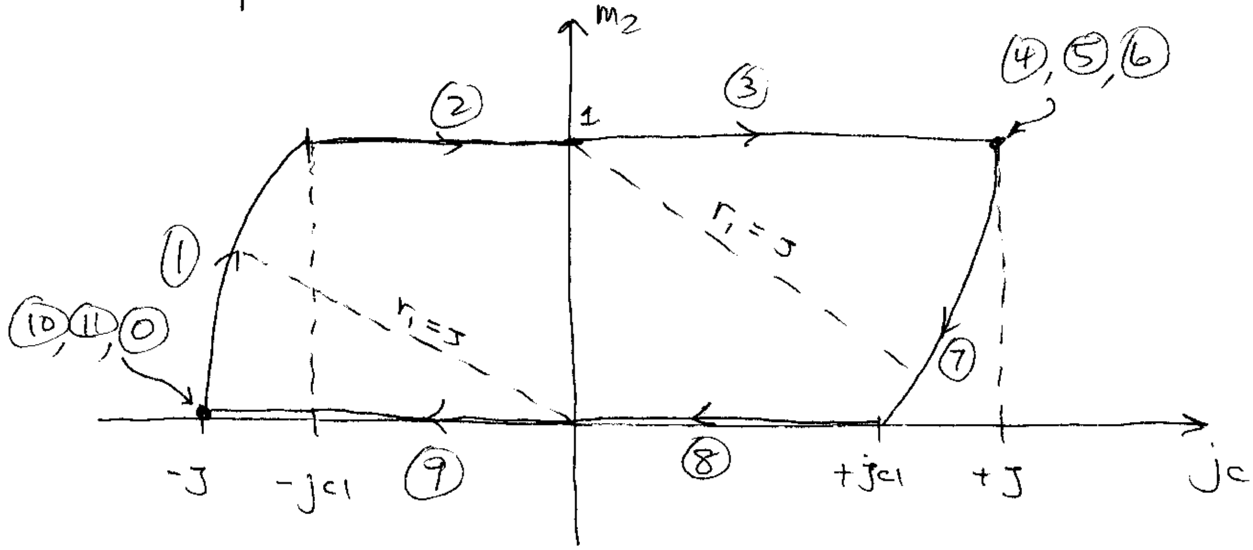
During this interval, the current $i_c = nI$ circulates around a loop containing the transformer primary winding, L_c, Q_1, and D_3. This current induces conduction loss in these elements.

This current is needed to induce zero-voltage switching during interval 7. However, if interval 6 is long in duration, then the conduction loss induced during interval 6 may be larger than the switching loss mitigated during interval 7. To obtain a high-efficiency design, the transformer turns ratio should be chosen so that $M = V/nV_g$ is only slightly less than 1. Small values of M lead to long interval 6 lengths, with increased conduction loss.

During interval 6, $v_2 = 0$, $i_c = nI$, $v_0 = 0$.

Subintervals 7 to 11 and 0 are symmetrical to subintervals 1 to 6.

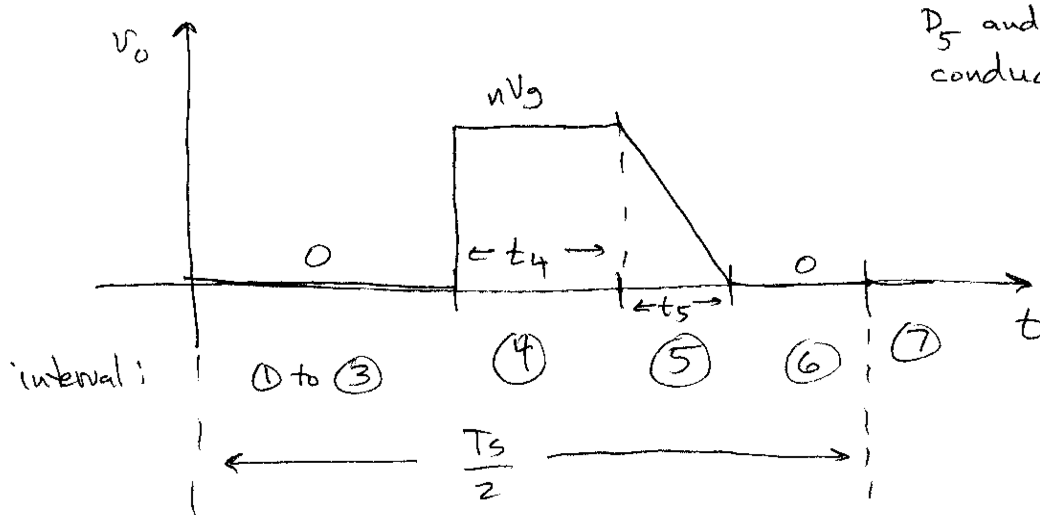
Complete state plane trajectory:



<u>Averaging</u>

$$\langle v_o \rangle = V = \frac{2}{T_s} \int_0^{\frac{T_s}{2}} v_o \, dt$$

note $v_o = 0$ whenever D_5 and D_6 both conduct.



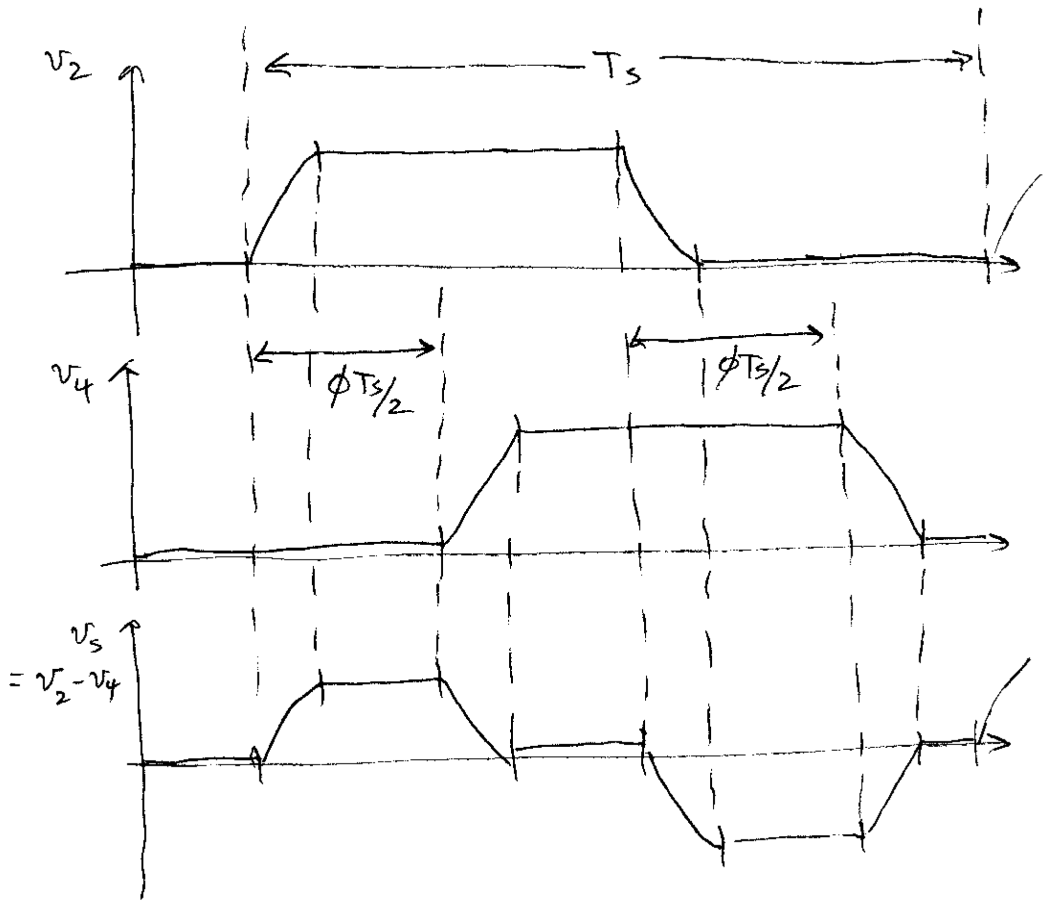
$$\langle v_o \rangle = \frac{2}{T_s} \cdot \left[nV_g t_4 + \frac{1}{2} nV_g t_5 \right]$$

Length of interval (4) depends on control input.

Phase shift Control:

Phase control variable ϕ performs the role of the duty cycle:

$$0 \le \phi \le 1$$



when $\phi = 0$, v_2 and v_4 are in phase, and output voltage is minimized.
when $\phi = 1$, v_2 and v_4 are of opposite phase, and output voltage is maximized.

$$\phi T_s/2 = t_1 + t_2 + t_3 + t_4$$

So $$t_4 = \frac{\phi T_s}{2} - t_1 - t_2 - t_3$$

Hence

$$\langle v_o \rangle = \frac{2}{T_s} n V_g \left[\frac{\phi T_s}{2} - t_1 - t_2 - t_3 + \frac{1}{2} t_5 \right]$$

$$M = \frac{V}{n V_g} = \frac{\langle v_o \rangle}{n V_g} = \phi - \frac{2}{T_s} \left[t_1 + t_2 + t_3 - \frac{1}{2} t_5 \right]$$

with $$t_1 = \frac{1}{\omega_0} \tan^{-1}\left(\frac{1}{\sqrt{J^2 - 1}} \right)$$

$$t_2 + t_3 = (nI + i_{c1}) \frac{L_c}{V_g}$$

$$t_5 = \frac{V_g}{nI} (C_{leg3} + C_{leg4})$$

substitute and normalize to obtain

$$M = \phi + \frac{F}{2\pi} \left[\frac{1}{J} - 2 \tan^{-1}\left(\frac{1}{\sqrt{J^2 - 1}} \right) - 2J + 2\sqrt{J^2 - 1} \right]$$

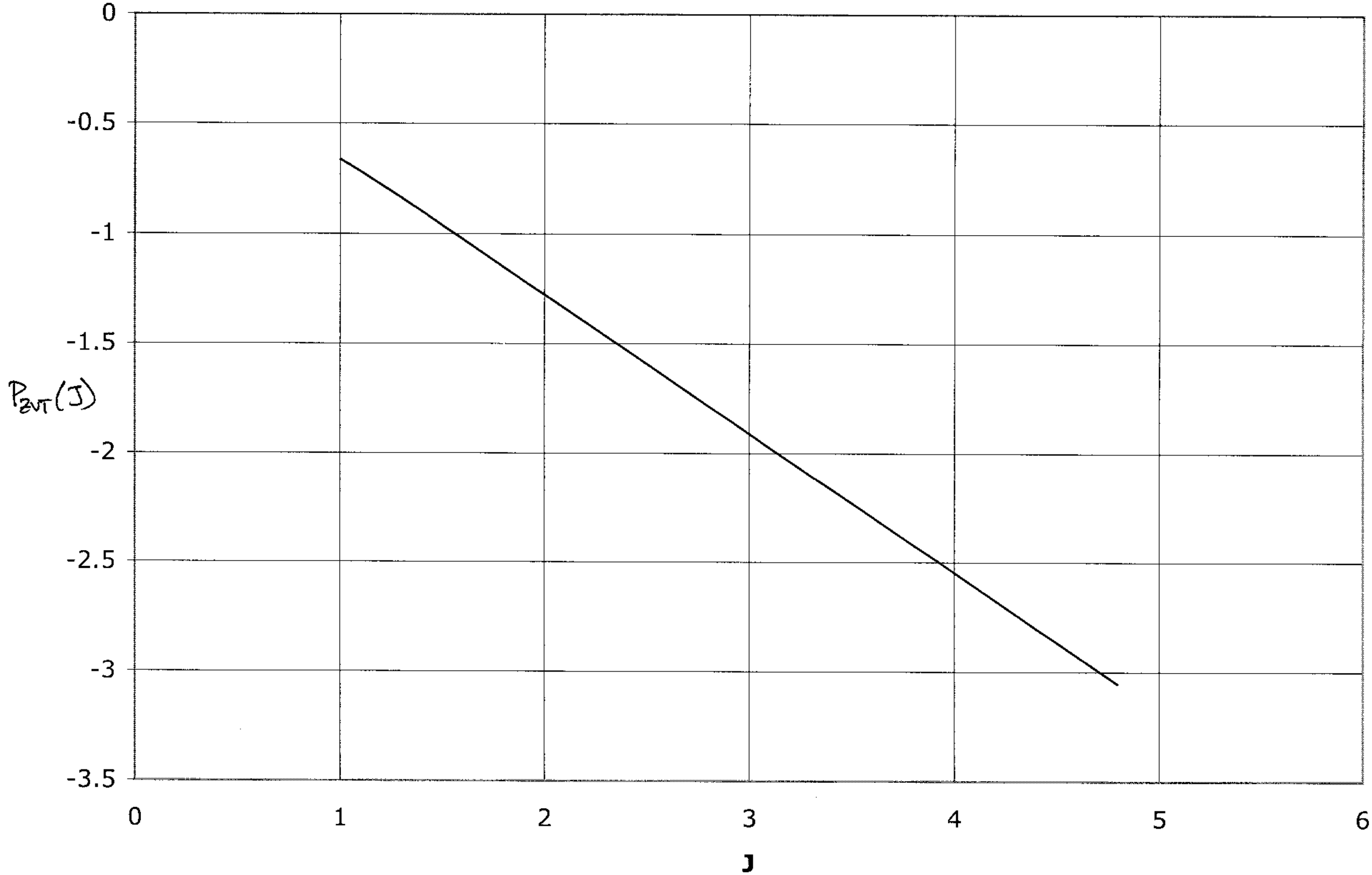
which is of the form with $J \geq 1$

$$M = \phi + F \, P_{ZVT}(J)$$

with $F = \frac{f_s}{f_o}$ and

$$P_{ZVT}(J) = \frac{1}{2\pi} \left[\frac{1}{J} - 2 \tan^{-1}\left(\frac{1}{\sqrt{J^2 - 1}} \right) - 2\left(J + \sqrt{J^2 - 1} \right) \right]$$

ZVT: $M=\frac{V}{nV_g}=\phi+F P_{ZVT}(J)$, $F=\frac{f_s}{f_0}$, $P_{ZVT}(J)=\frac{1}{2\pi}\left[\frac{1}{J}-2\tan^{-1}\frac{1}{\sqrt{J^2-1}}-2\left(J+\sqrt{J^2-1}\right)\right]$



$P_{ZVT}(J)$ is negative and not very large in magnitude.

Also, if the resonant transitions are a small fraction of the switching period, then $F \ll 1$.

Hence $|F P_{ZVT}(J)| \ll 1$, and $M \approx \emptyset$.

The exact M is slightly smaller than $\emptyset$.