< Switching Power Amplifier >

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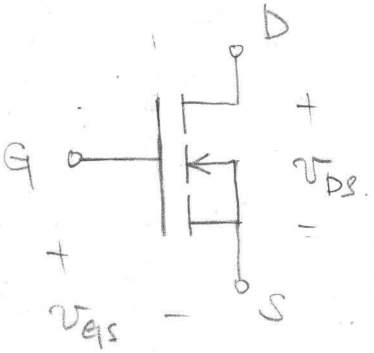
- Objectives
  - MOSFET
  - Half-bridge stage
  - H-bridge Inverter.

- Metal-Oxide-Semiconductor Field-effective transistor

  We focus on n-channel, enhancement-mode MOSFET.



<u>Symbol meaning</u>

- Gate is AC coupled : $i_G = 0$
- Arrow : p-type body $\rightarrow$ n-channel
- Body-source short : "Body diode"
- <u>Dotted line</u> : enhancement-mode (normally off)
  ↳ often drawn as a <u>solid line</u> for brevity
  depletion-mode (normally on)

<u>Terminal variables</u>

- Voltage : v_{GS}, v_{DS}
- Current : i_G, i_D, i_S ($i_G = 0$ at DC $\Rightarrow$ $i_D = i_S$)

<u>Terminal Relations</u>

① Cutoff region. ($v_{GS} < V_{th}$)

$$i_D = 0$$

② Saturation region ($v_{GS} > V_{th}$, $v_{DS} > v_{GS} - V_{th}$)

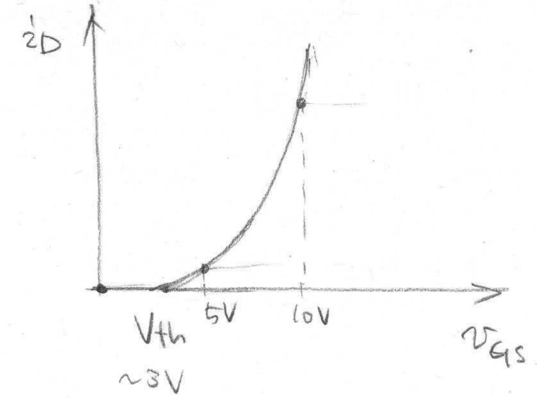
$$i_D = \frac{1}{2}K\cdot(v_{GS} - V_{th})^2 \rightarrow g_m \triangleq \frac{di_D}{dv_{GS}} = K(v_{GS} - V_{th})$$

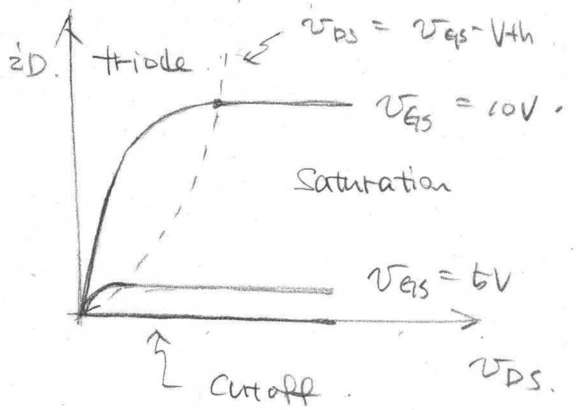
(Similar to Active mode in BJT)

- MOSFET can be used as a VCCS

$\because$ i_D is insensitive to v_{DS} in saturation region.

< Input characteristic >   < Output characteristic >





③ Triode region ($v_{GS} > V_{th}$, $v_{DS} < v_{GS} - V_{th}$)

$$i_D = K\left[(v_{GS} - V_{th})\, v_{DS} - \frac{1}{2} v_{DS}^2\right]$$

$$\simeq \underbrace{K(v_{GS} - V_{th})}\, v_{DS}$$

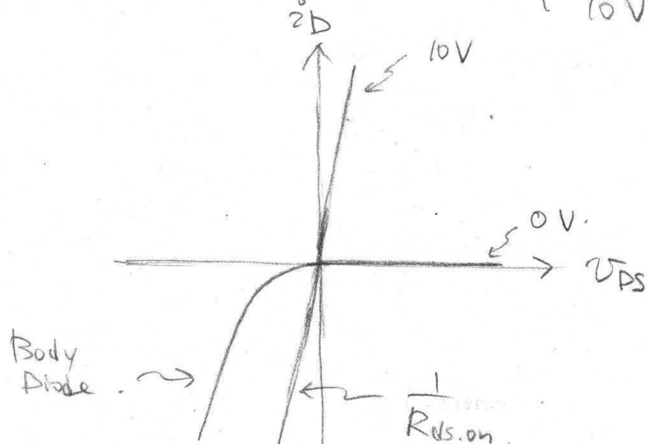
$$\triangleq \frac{1}{R_{DS,on}} \qquad R_{DS(on)} = \frac{1}{K(v_{GS} - V_{th})}$$

→ Varies with v_{GS}

- MOSFET as a "power switch".

Suppose $v_{GS} = \begin{cases} 0 & \text{(Switch off)} \\ 10V & \text{(Switch on)} \end{cases}$

< Equivalent circuit >



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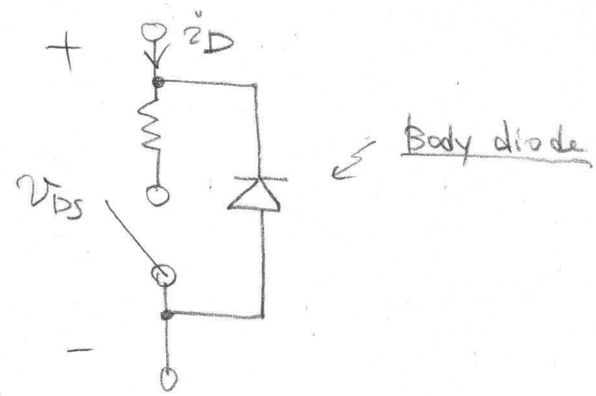
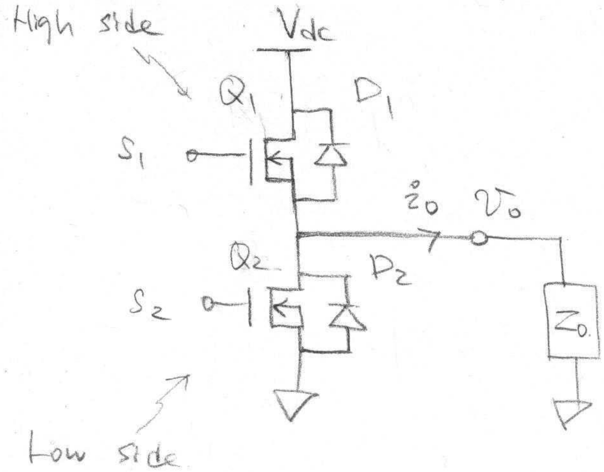


- Modern MOSFETs have fast-enough body diodes (fast recovery)
- Block $+v$ / Conduct $\pm i$

∘ Half-bridge stage (Totem pole circuit)



- Can make a unipolar two quadrant ($+v_o$, $\pm i_o$) voltage source.
- Versatile building block for various switching power converters.
- Available as a single package with integrated gate drive.

∘ State Table

k	S_1	S_2	v_o	Conduction
0	0	0	0 / V_{dc}	D_2 ($i_o>0$) / D_1 ($i_o<0$)
1	1	0	V_{dc}	Q_1 } Lower P_{diss} than k=1.
2	0	1	0	Q_2
3	1	1	X	Shoot through

- Toggle between k = 1 and k = 2. "Complementary switching"
- Never use k = 3 "shoot through"
- Insert k=0 between k=1 ⟷ k=2 to avoid k=3. "Dead time"

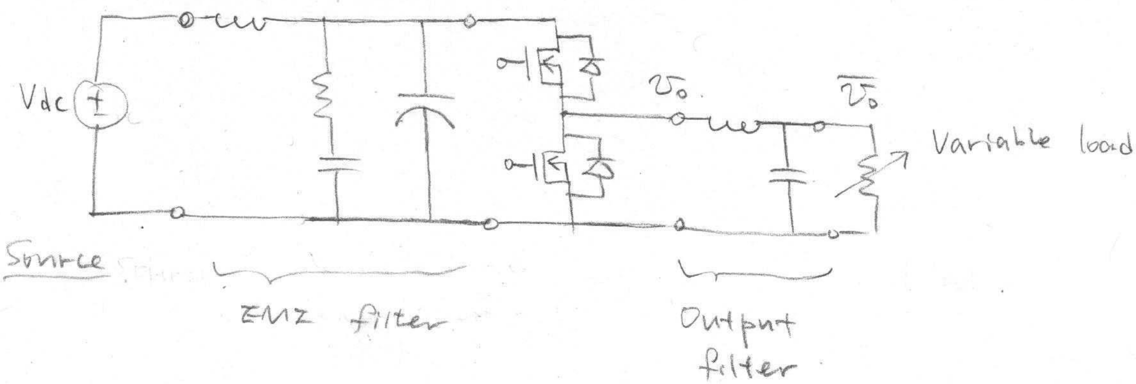
∘ State Variable

- Let us introduce a boolean variable "a" and control the two switches in a complementary manner.

$$a = S_1 = \overline{S_2} \Rightarrow \begin{cases} a=0 : & v_o = 0 \\ a=1 : & v_o = V_{dc} \end{cases}$$

NOT {S_2}

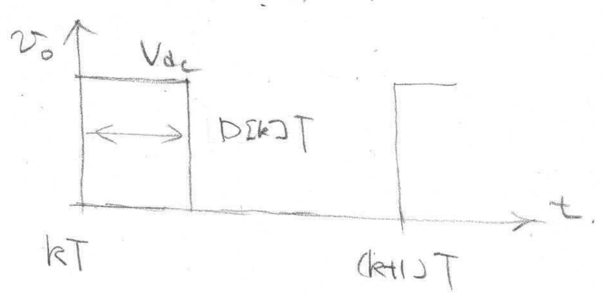
- Synchronous Buck Converter (dc/dc down conv.)



- State Table

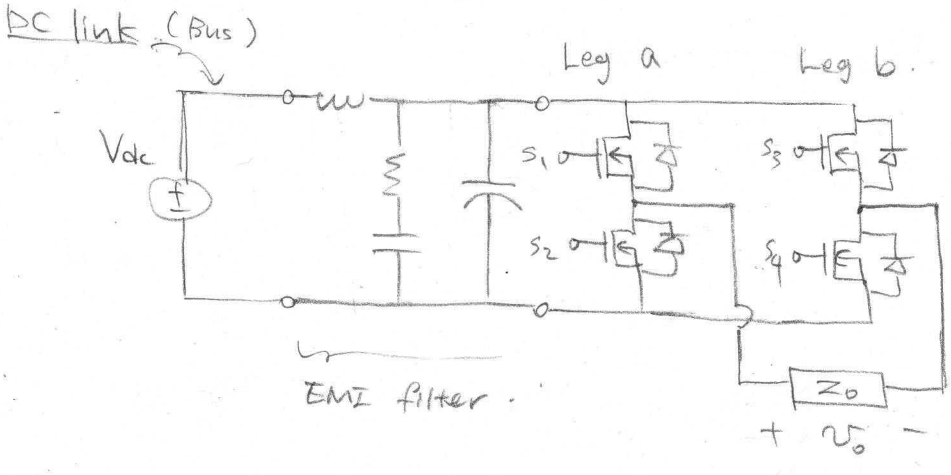
n	a	v_o
1	1	Vdc
2	0	0.

- Output waveform (n=1 ⟺ n=2)



$$\overline{v_o}[k] = \frac{1}{T}\int_{kT}^{(k+1)T} v_o(t)\,dt = D[k]\,V_{dc}$$

- H-bridge Inverter (dc/ac converter)



Can make bipolar four quadrant ($\pm v_o, \pm i_o$) Voltage source

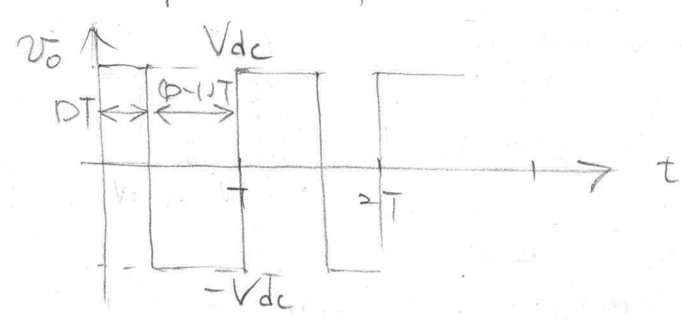
"Bridge" between legs

- State Table

State Vector → $V_1 = [0\ 0]^T$

n	a	b	v_o
0	0	0	0
1	1	0	Vdc.
2	0	1	-Vdc
3	1	1	0

- Output waveform. (n = 1 ⟺ n=2)



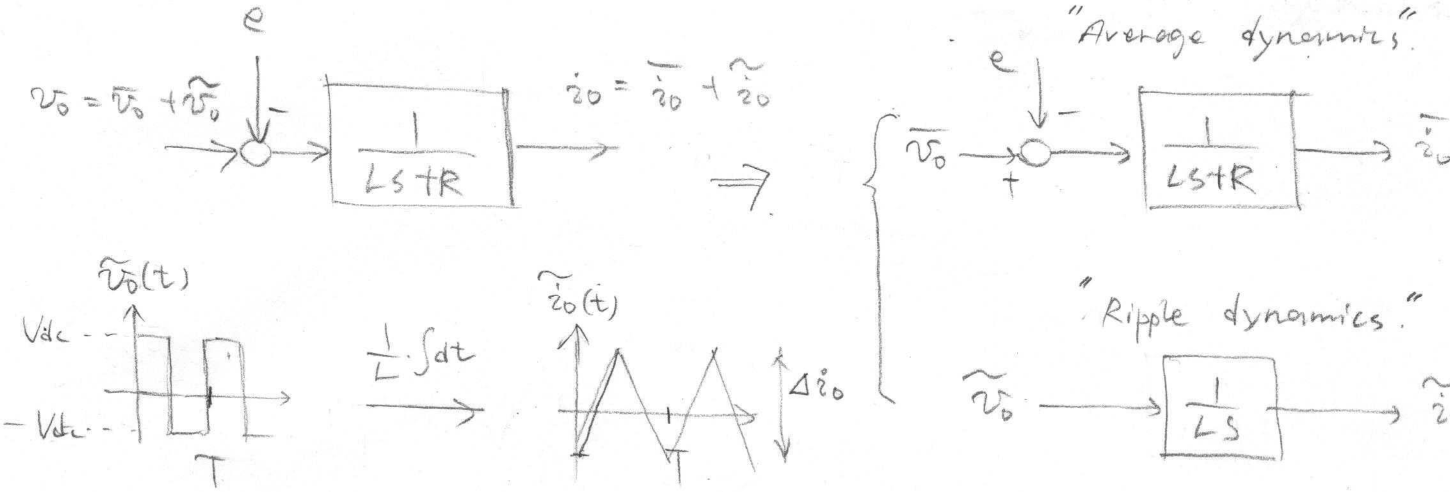
- Duty ratio Control.

Togle the state between n=1 and n=2. ; $D \triangleq \frac{t_1}{T}$

$$\bar{v}_o = \frac{V_{dc}}{T}\left(D \cdot T + (D-1)T \right)$$

$$= (2D-1)\, V_{dc}.$$ Note that $\bar{v}_o = 0$ when $D = 0.5$

- Current ripple



when $D = 0.5$ (worst-case ripple).

$$\Delta i_o = \frac{V_{dc}}{L} \cdot DT$$

$$= \frac{V_{dc}}{2L} \cdot \frac{1}{f_s}$$

Example : $\frac{30\ \mathrm{V}}{2 \times 1.6\ \mathrm{mH}} \frac{1}{40\ \mathrm{kHz}} \simeq \frac{10}{40} = \underline{250\ \mathrm{mA}}$

- Current ripple causes { torque ripples. → vibration; core losses (Hysteresis, eddy-current)

- Remedy
  - Insert series inductors (cost : current slew rate ↓)
  - Increases the switching frequency (cost : switching loss ↑)