EEL 5245 POWER ELECTRONICS I

Lecture #3: Chapter 2

Switching Concepts

Discussion Topics

- **Homework Assignment #1**
- **Need for Switching in Power Electronic Converters**
  - **Example on Efficiency Comparison**
- **Ideal Switch Characteristics**
- **Comparison to Practical Switch**
- **Power Loss in Practical Switch**
- **Several Examples on Switch Loss Calculation (Conduction and Switching components of Loss)-(Batarseh)**

Homework Assignment #1

Exercises:

E2.1, E2.3

Problems:

P2.2, P2.3, P2.4, P2.6

Due Wednesday, September 3, 2014

Submit via email

Homework Corrections-Hw #1

- **Direct Homework questions to:**
- **Answers per solution manual and need to be verified**
- **Problem 2.2- R is 5Ω**
  - **(a.) Ans. -80V**
  - **(b.) Ans. 1600W**
  - **(c.) Ans. 100%**
- **Problem 2.3**
  - **Vo,avg=2*Delta*Idc*R**
- **Problem 2.4-**
  - **Like class example (easier), Find Psw(t), Pavg=.302W**

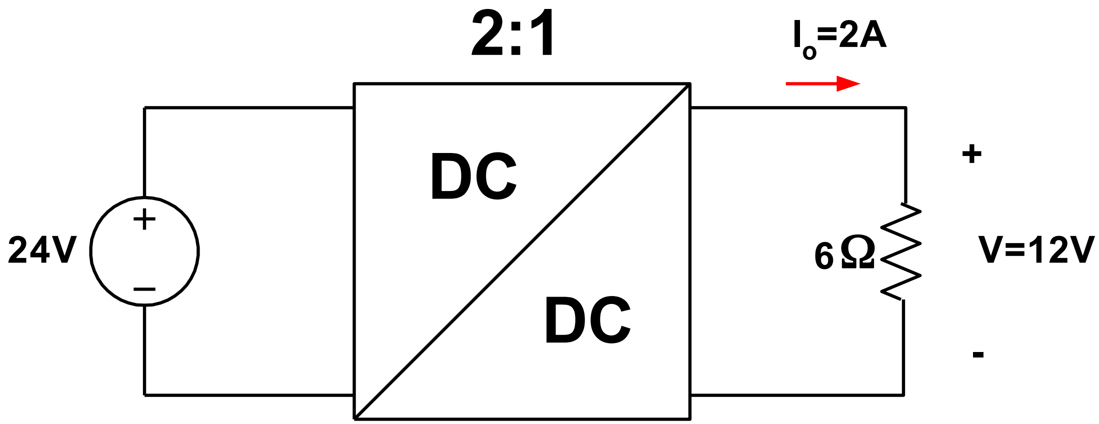
Homework Corrections-Hw #2

- **Answers per solution manual and need to be verified**
- **Problem 2.8- Von=.7V**
  - (a.) Ans. Psw=32.5W
  - (b.) Ans. Pcond=9.59W
- **Problem 2.10**
  - Do (a.)-(c.) only, skip (d)
  - (b.) Ans. Po,avg=.5*fs*Voff*Ion*(2*td+tf+tr)
  - (c.) Ans. Po,avg=54W

Need for Switching

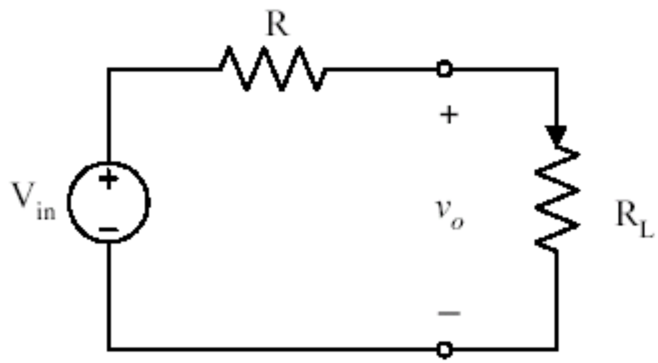
- **Why use semiconductor devices as switches?**
  - **Allows better output control**
  - **Allows for improved efficiency**
    - **Ideally 100%**
- **What are effects of poor efficiency?**
  - **Energy costs**
  - **Design complications**
  - **Reduce reliability-(More losses mean more heat)**
  - **More component design**
    - **Heat transfer**
    - **Protection**

Theoretical Efficiency Example



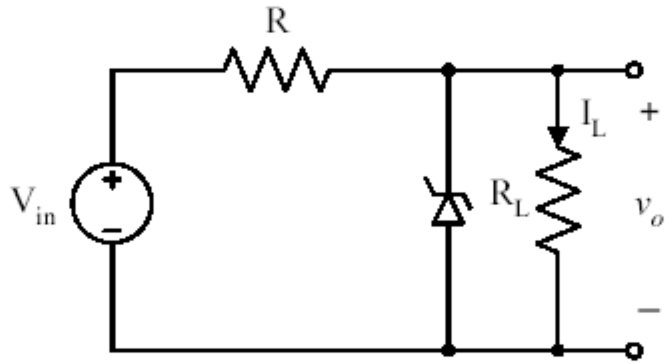
- We' ll do an example to underscore why switching is the most energy efficient choice
- Consider the design of a DC-DC converter as shown above
- Design requires 24V step down to 12V across a 6 Ohm resistive load
- Let' s investigate, some possible options

Theoretical Efficiency Example Voltage Divider



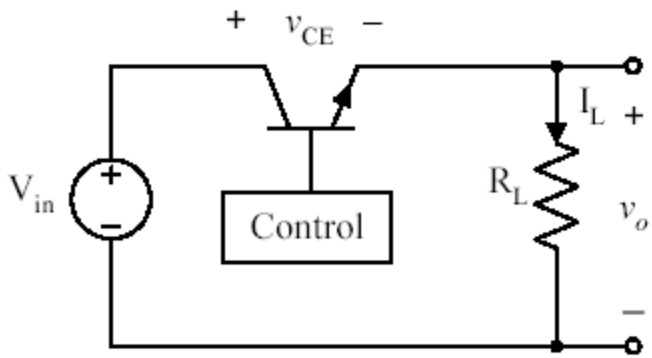
- A simple voltage divider can do job
- R must be set to 6 Ω
- Load cannot change-R fixed so no opportunity for control
- Losses are high η=50%

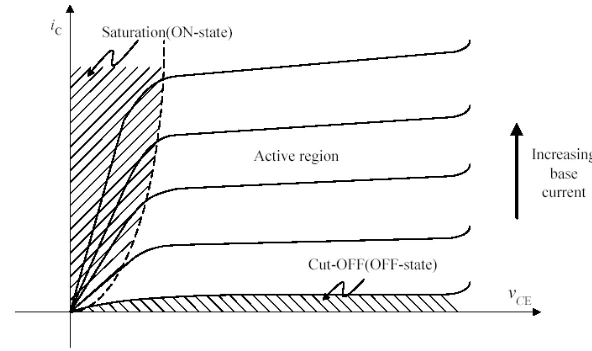
Theoretical Efficiency Example
Zener Regulator



- Need some control (regulation)
- A Zener Regulator will allow for load variation
- Assume Vz=12V, Iz@12V=.2A , Rdrop=5.5Ω
- Pin=Pout+Prdrop+Pzener=24W+26.2W+2.4W=52.6W
- η=46%

Theoretical Efficiency Example
Linear Regulator

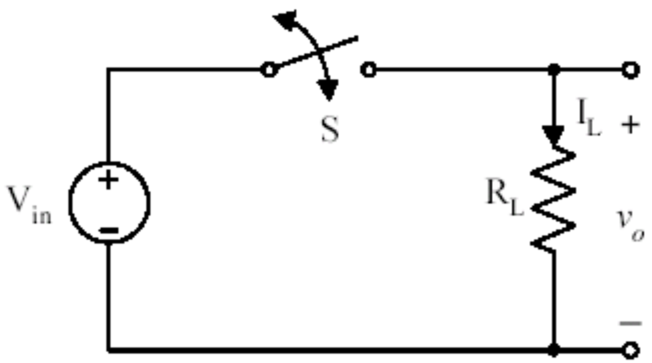


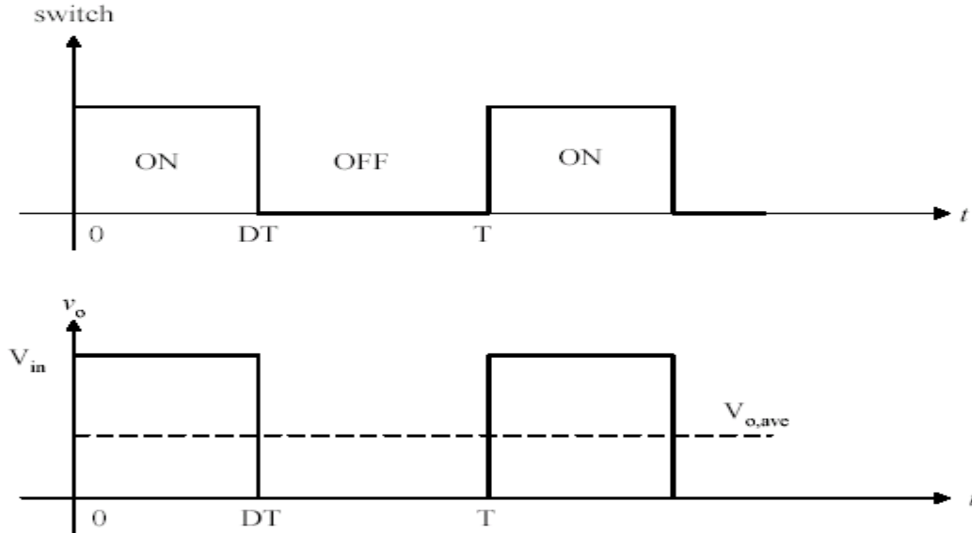


- **Drop resistor inefficient means**
- **Direct source connection is preferable**
- **Try linear regulator**

  (Similar to implementation 7805, LM317 etc.
- **Assume Vce=12V**
- **Pin=Pout+Pnpnloss=24W+24W=50W**
- **η=50%**

Theoretical Efficiency Example
Duty Ratio Controlled Switch





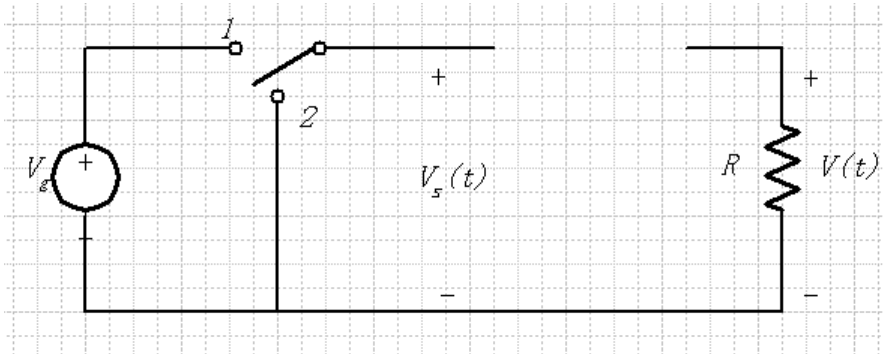
$$V_{o,ave} = \frac{1}{T}\int_0^{TD} V_{in}\, dt = V_{in} D$$

- **Instead of operating transistor in active mode try using as switch**
- **Low Pass filter required to extract DC**
- **η=100%**

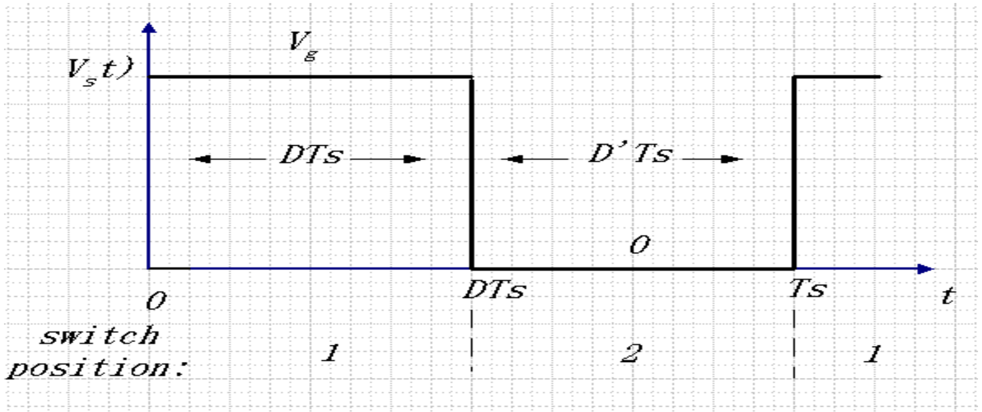
Circuit Implementation
Duty Ratio Controlled Switch-SPDT

SPDT switch changes dc component

- **Note-all power semiconductor devices act as SPST switch**



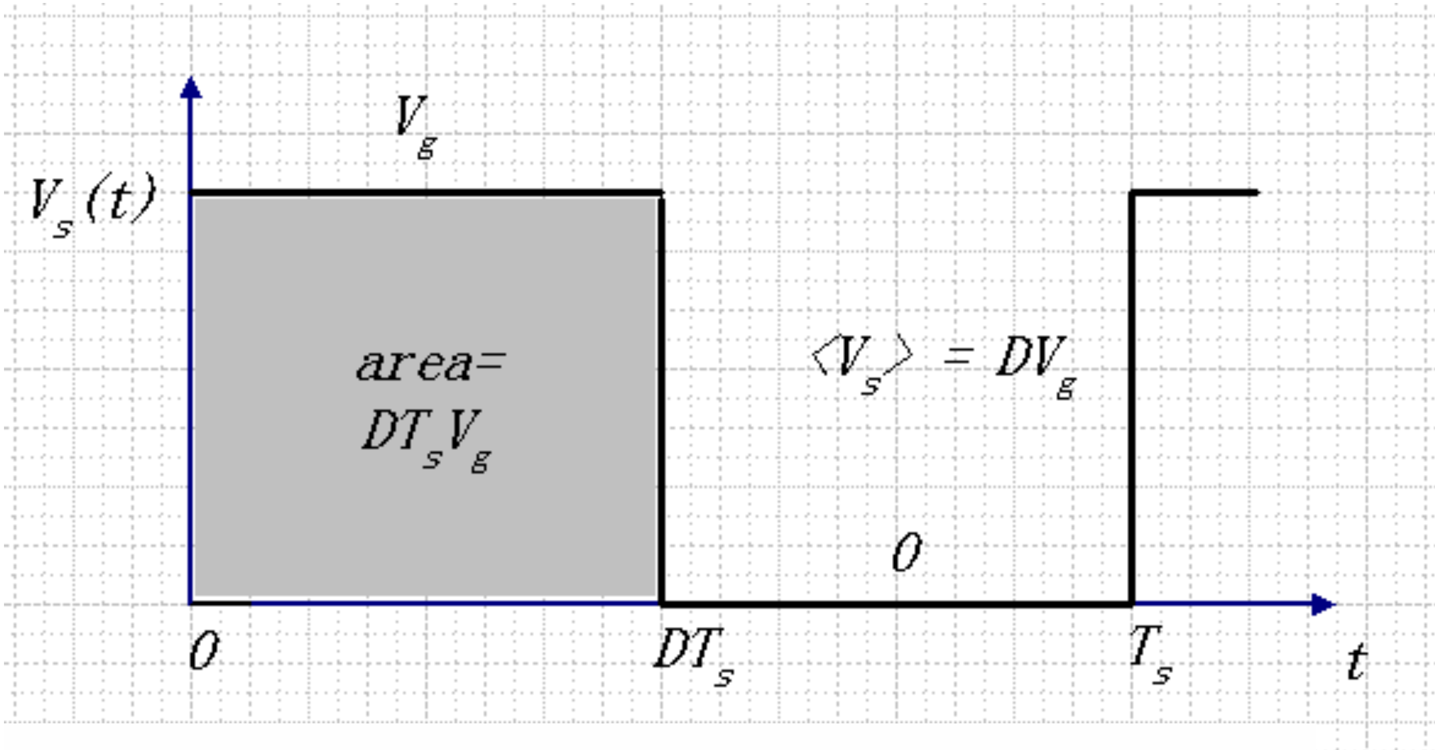
Switch output voltage waveform



Duty cycle *D*:
$0 \le D \le 1$

complement D':
$D' = 1 - D$

DC Component

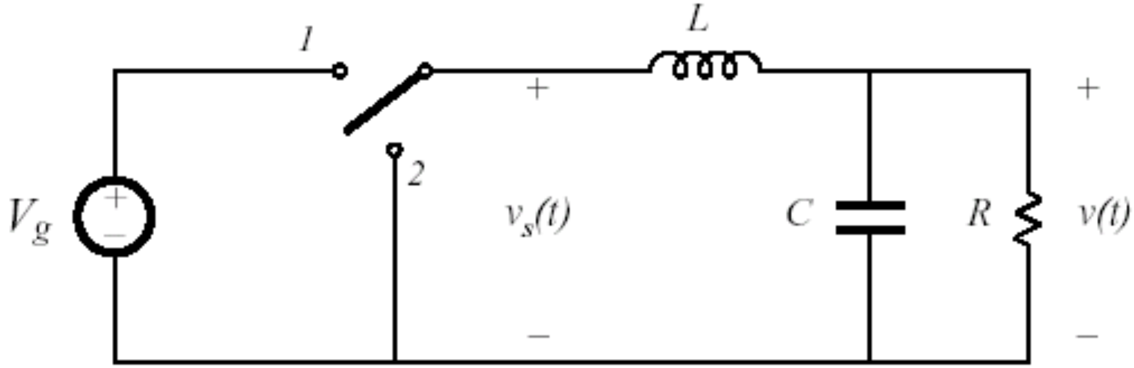


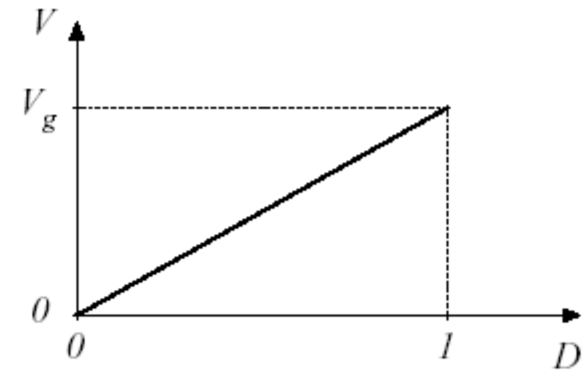
Fourier analysis: Dc component = average value

$$\langle v_s \rangle = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt$$

$$\langle v_s \rangle = \frac{1}{T_s}(DT_sV_g) = DV_g$$

Step Down Converter-Buck



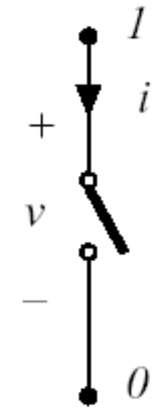


- **Low Pass extracts DC**
- **Position 2 allows for current "freewheeling"**
- **Vo can be controlled by adjusting D (Switching Period/ Frequency Fixed), Vo/Vin = D**
- **Ideally, is no switch/filter loss, η=100%**
  - **We assume an ideal switch here**

Summary of Example

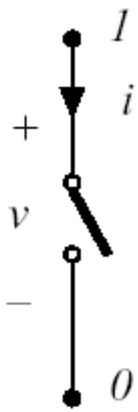
- Step down converter (Buck) exemplifies how waveform “chopping” allows control output
- Waveform modification by “chopping” is fundamental premise in Power Electronics
- If switch ideal, no losses
- By controlling D, Vo is controlled, independent of load
- Clearly, for an ideal switch, this example is the best approach
- In reality, switch not ideal (switching/conduction losses)
- “Chopping” means harmonics at both input/output (EMI)
- Is the assumption of an ideal switch reasonable?

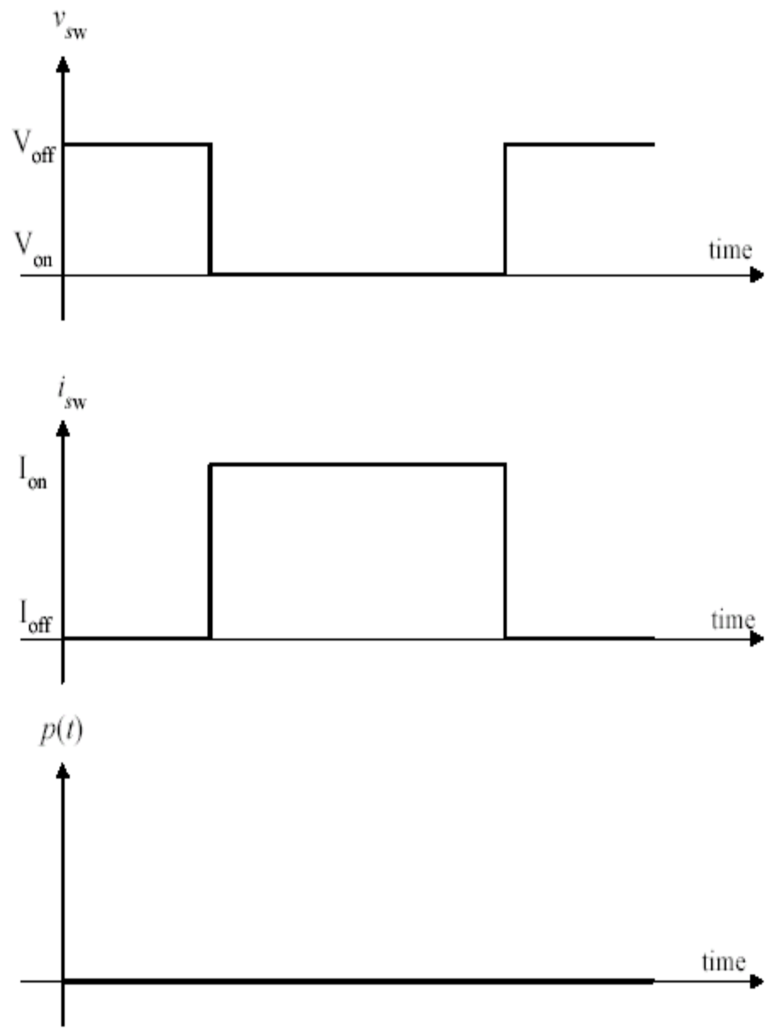
Ideal Switch Characteristics



- **Zero on-state resistance**
  - **No forward voltage drop when on**
- **Infinite off-state resistance**
  - **No leakage current when off**
- **Current limitless when on-either direction**
  - **Conduction current a function of external components only**
- **No limit on amount of voltage across switch when off**
  - **Blocking voltage infinite (forward or reverse)**
- **Switch can transition from on-off or off-on instantaneously when commanded to**

Ideal Switch i-v Characteristics (Transition)





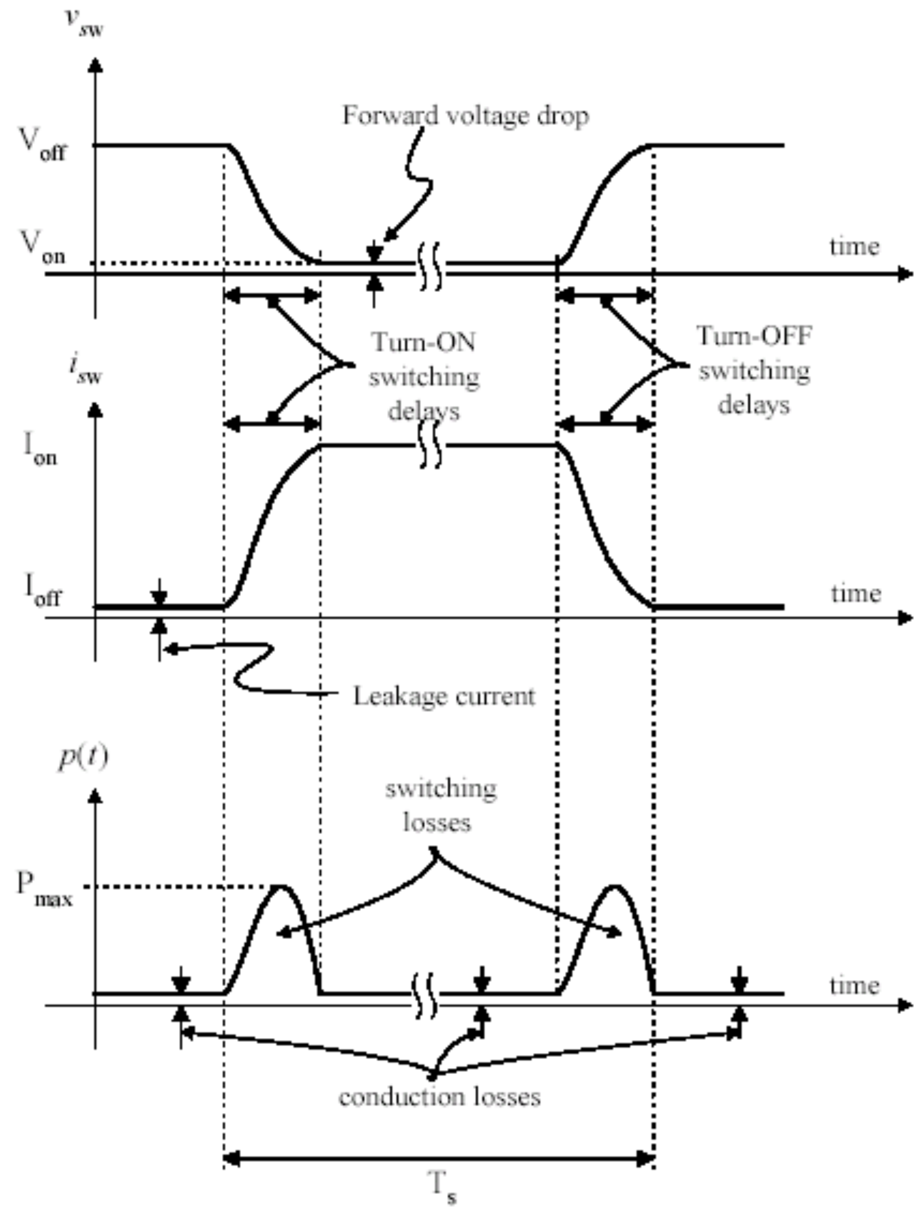
- **Previous desirable conditions mean, no power loss by any mechanism (conduction, leakage, or switching)**
  - **Switch transition-No overlap**
  - **Von=0V, Ioff=0A**

Practical Switch

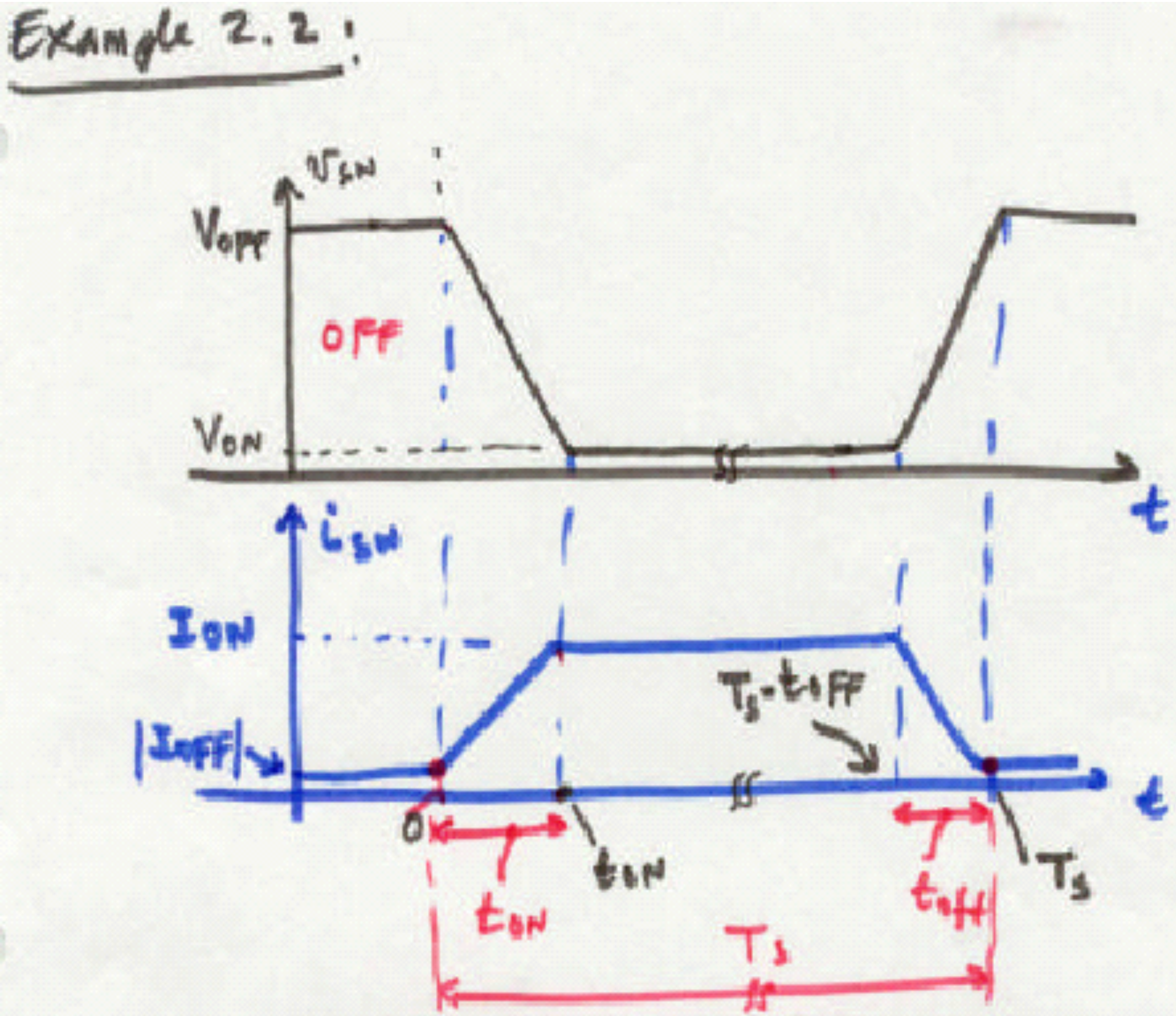
- **Although Semiconductor Industry has produced amazing devices, the "real world" switch is not ideal**
  - **Limited conduction current when the switch on, limited blocking voltage when the switch is in the off**
    - **Both are directional in practical switch**
  - **Limited switching speed that caused by the finite turn-*on* and turn-*off* times**
    - **Real world (Semiconductor) switches are charge driven**
  - **Finite, nonzero *on*-state and *off*-state resistances**
    - **There is a I^2R loss when on and some leakage when off (very small)**

Practical Switch i-v Characteristics (Transition)

- ***<u>This is root cause of the single major source of loss in PE converters</u>***
  - ***<u>Conduction- When switch is in on state (off state too, to a lesser degree)</u>***
  - ***<u>Switching Losses- When switch is transitioning from on to off or off to on</u>***



Switch Loss Example



- Derive expression for instantaneous power, $p(t)=v_{sw}*i_{sw}$
- Determine average power dissipation over one switching cycle, Ts

Switch Loss Example

$$
i_{sw} = \begin{cases} \dfrac{t}{t_{ON}}(I_{ON} - I_{OFF}) + I_{OFF} & 0 \le t < t_{ON} \\ I_{ON} & t_{ON} \le t < T_s - t_{OFF} \\ -\dfrac{t - T_s}{t_{OFF}}(I_{ON} - I_{OFF}) + I_{OFF} & T_s - t_{off} \le t < T_s \end{cases}
$$

$$
v_{sw} = \begin{cases} -\dfrac{V_{OFF} - V_{ON}}{t_{ON}}(t - t_{ON}) + V_{ON} \\ V_{ON} \\ \dfrac{V_{OFF} - V_{ON}}{t_{OFF}}\left(t - (T_s - t_{off})\right) + V_{ON} \end{cases}
$$

Switch Loss Example

The instantaneous power, $p(t)$, is given by

$$p(t) = i_{sw} v_{sw}$$

Assum $I_{off} \approx 0$ & $V_{on} \approx 0$

$$p(t) = \begin{cases} -\dfrac{V_{OFF} I_{ON}}{t_{ON}^2}(t - t_{ON})t & 0 \le t < t_{ON} \quad \leftarrow p_1 \\ V_{ON} I_{ON} & t_{ON} \le t < T_s - t_{OFF} \quad \leftarrow p_2 \\ -\dfrac{V_{OFF} I_{ON}}{t_{OFF}^2}(t - (T_s - t_{OFF}))(t - T_s) & T_s - t_{OFF} \le t < T_s \quad \leftarrow p_3 \end{cases}$$

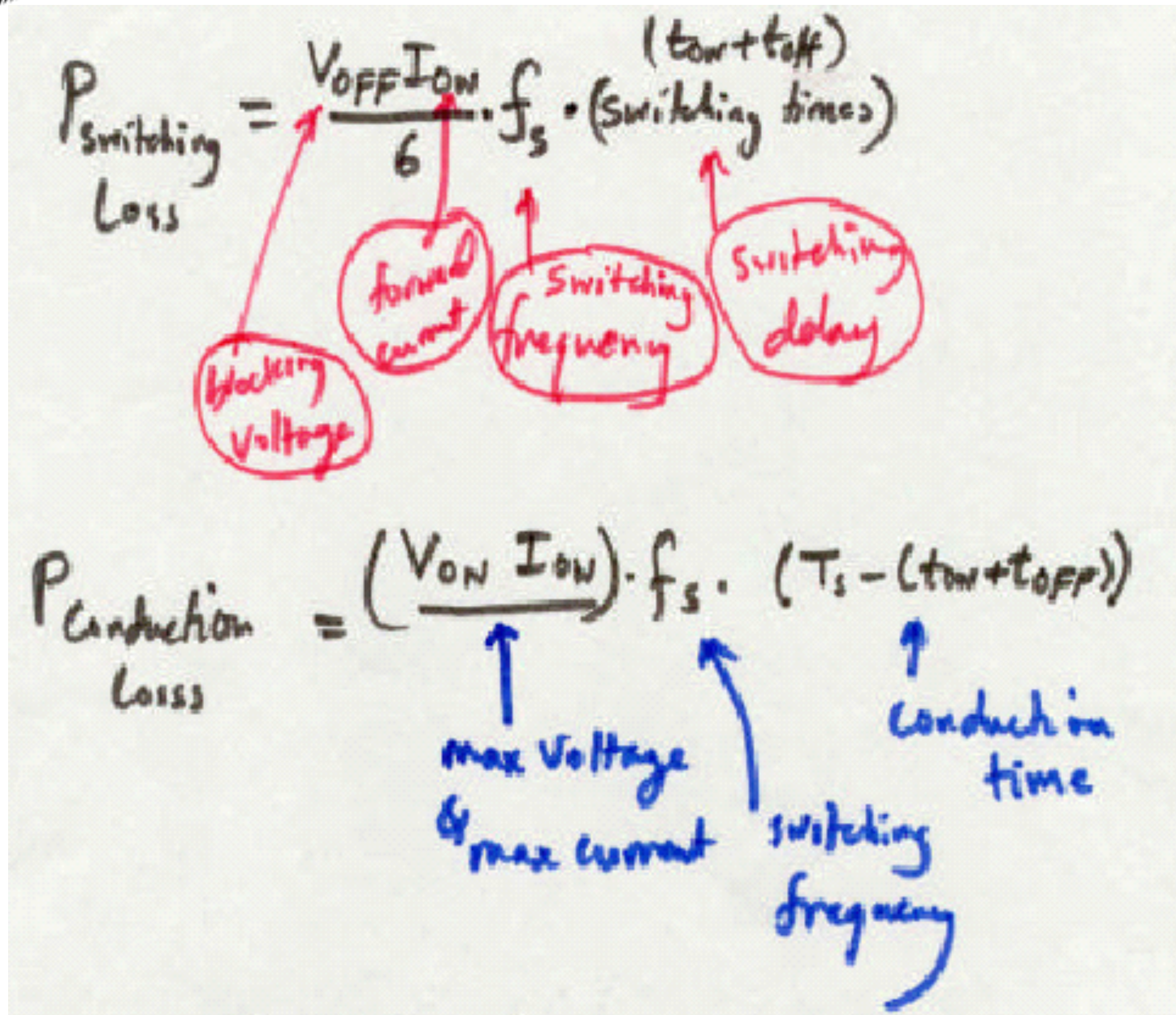
Switch Loss Example

c) $$P_{ave} = \frac{1}{T_s}\int_0^{T_s} p(t)\,dt$$

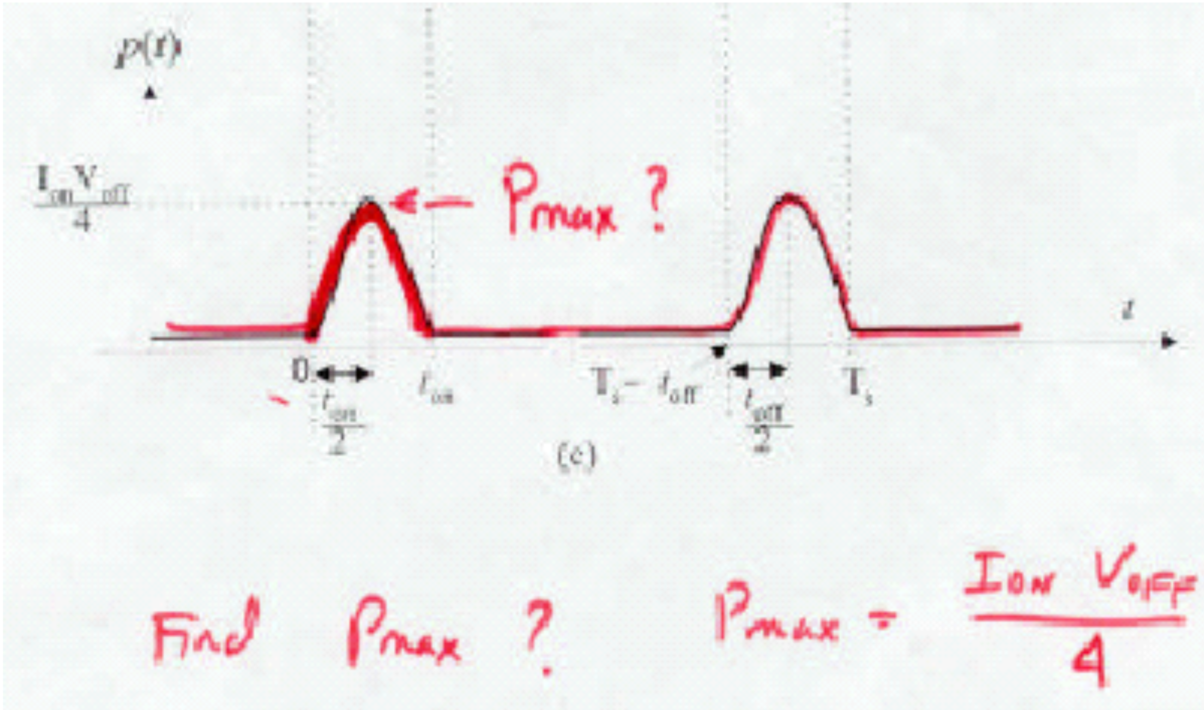
$$= \frac{1}{T_s}\left[\int_0^{t_{on}} P_1(t)\,dt + \int_{t_{on}}^{T_s - t_{off}} P_2\,dt + \int_{T_s - t_{off}}^{T_s} P_3\,dt\right]$$

$$= \frac{V_{OFF} I_{ON}}{6T_s}(t_{on} + t_{OFF}) + \frac{V_{ON} I_{ON}}{T_s}(T_s - (t_{on} + t_{off}))$$

Switch Loss Example

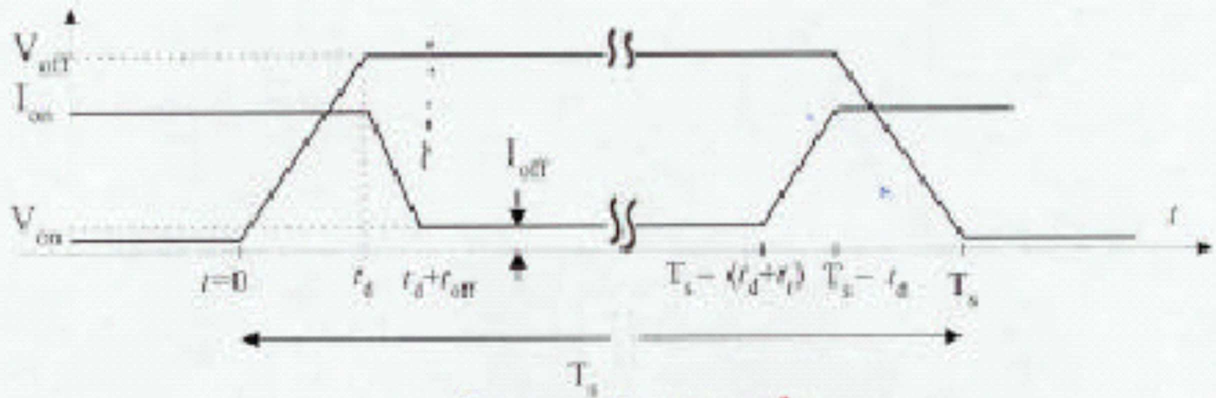


Switch Loss Example



Another Switch Loss Example

Exercise 2.1: Determine the average Power dissipated in a switch that has the following switching characteristics:



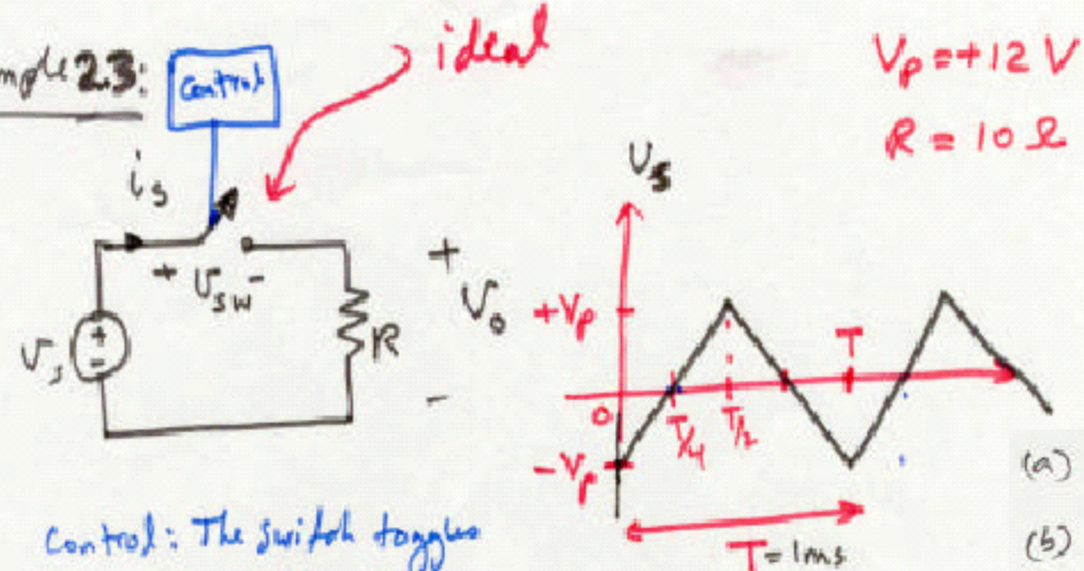
(Inductive Load)

Fig. E2.1

$$P_{ave} = \frac{V_{off} I_{on}}{2} (2t_d + t_f + t_r) f_s$$

Example on Vo Control

Example 2.3:



Control: The switch toggles every time the input voltage crosses zero.

Assume the switch was initially (t = 0) open.

(a) sketch i_s & V_o.

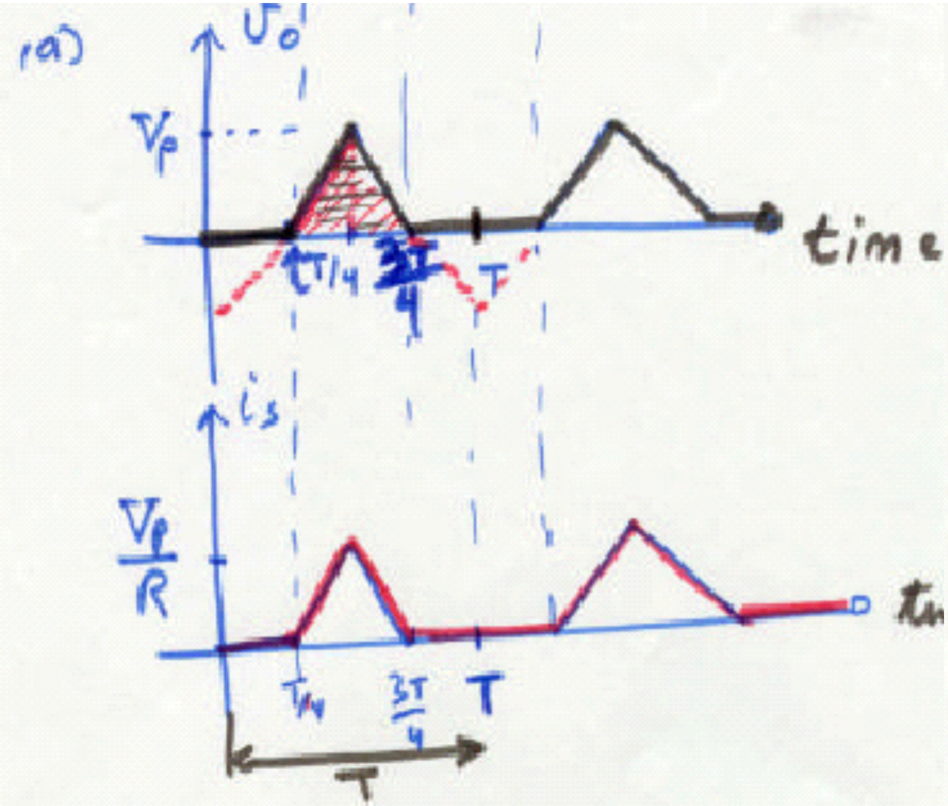
(b) Calculate the average and rms values values for V_o.

(c) Calculate the average input power and the average output power.

(d) Repeat for T = 1μs

e) Repeat the above by assuming the switch has 1V forward voltage drop.

Example on Vo Control



(b) The average output voltage,

$$V_{o,ave} = \frac{1}{T}\int_0^T v_o\,dt = \frac{1}{T}\int_{T/4}^{3T/4} v_o\,dt =$$

$$= \frac{1}{T}\left[\frac{1}{2}\,\frac{T}{2}\cdot V_p\right] = \frac{V_p}{4} = 3V$$

use $V_p = 12V$.

$$V_{o,rms} = \sqrt{\frac{1}{T}\int_0^T v_o^2\,dt}$$

$$= \sqrt{\frac{1}{T}\left[\int_{T/4}^{T/2}\left(\frac{4V_p}{T}t - V_p\right)^2 dt + \int_{T/2}^{3T/4}\left(-\frac{4V_p}{T}t + 3V_p\right)^2 dt\right]}$$

$$= \frac{V_p}{\sqrt{6}} \approx 4.9V$$

Example on Vo Control

k) $P_{in_{ave}} = \frac{1}{T}\int_0^T i_s v_s \, dt = \frac{1}{TR}\int_{T/4}^{3T/4} v_s^2 \, dt$

$$= \frac{V_p^2}{6R} = \frac{12^2}{6 \times 10\Omega} = 2.4\,W$$

$$P_{out_{ave}} = \frac{1}{T}\int_0^T i_o v_o \, dt = \frac{1}{T}\int_0^T i_s V_o \, dt$$

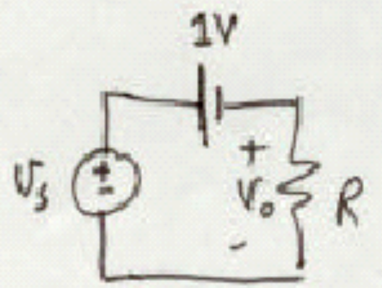
$$= \frac{1}{T}\left[\frac{1}{R}\int_{T/4}^{T/2} v_o^2 \, dt + \frac{1}{R}\int_{T/2}^{3T/4} v_o^2 \, dt\right]$$

$$= \frac{V_p^2}{6R} = 2.4\,W$$

$\eta = 100\%$ (Because of ideal diode)

Example on Vo Control

(e) Assume the switch has 1V drop.



$$V_o = V_s - 1V$$

$$V_{o,ave} = \frac{1}{T}\int_0^T V_o\,dt$$

$$= \frac{1}{T}\left[\int_{T/4}^{T/2}\left(\frac{4V_p}{T}t - V_p - 1\right)dt + \int_{T/2}^{3T/4}\left(-\frac{4V_p}{T}t + 3V_p - 1\right)dt\right]$$

$$= \frac{V_p}{4} - \frac{1}{2} = 2.5V$$

$$V_{o,rms} = \sqrt{\frac{1}{6V_p}\left[(V_p-1)^3 + 1\right]}$$

$$\approx 4.3V$$

$$P_{in,ave} = \frac{1}{4R}\left(\frac{2V_p^2}{3} - 1\right)$$

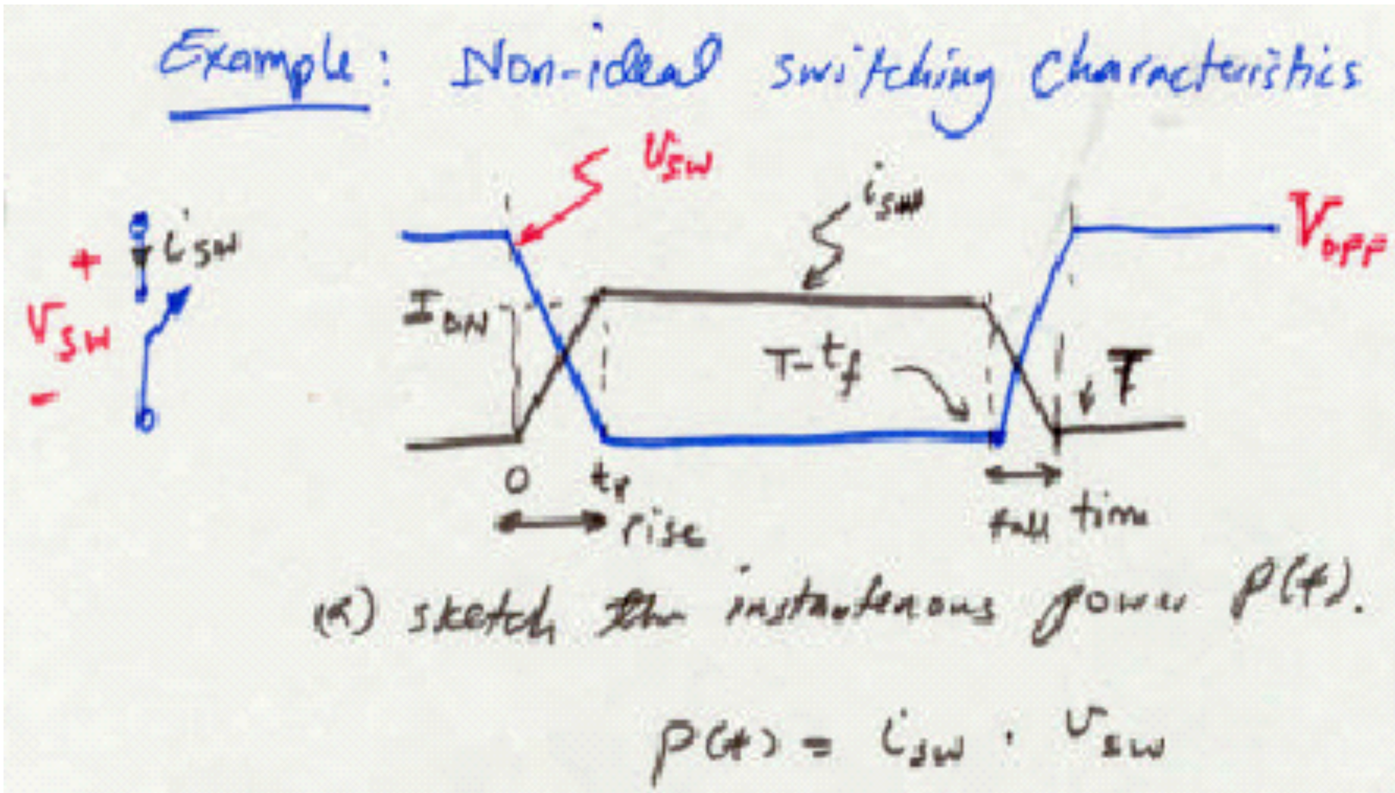
$$= 2.375\,W$$

$$P_{o,ave} = \frac{1}{R6V_p}\left[(V_p-1)^3 + 1\right] = 1.85\,W$$

$$\eta = \frac{P_{out,ave}}{P_{in,ave}}100\% = \frac{1.85}{2.375}100\%$$

$$\approx 77.9\%$$

Another Switch Loss Example (Pmax)



Another Switch Loss Example (Pmax)

i) For $0 < t \le t_r$

$$i_{sw}(t) = \frac{I_{ON}}{t_r}(t-0)$$

$$v_{sw}(t) = -\frac{V_{OFF}}{t_r}(t-t_r)$$

$$P_i(t) = i_{sw} v_{sw}$$

$$= -\frac{I_{ON} V_{OFF}}{t_r^2}(t-t_r)t$$

ii) For $t_r < t \le T_s - t_f$

$$i_{sw} = I_{ON}$$

$$v_{sw} = 0$$

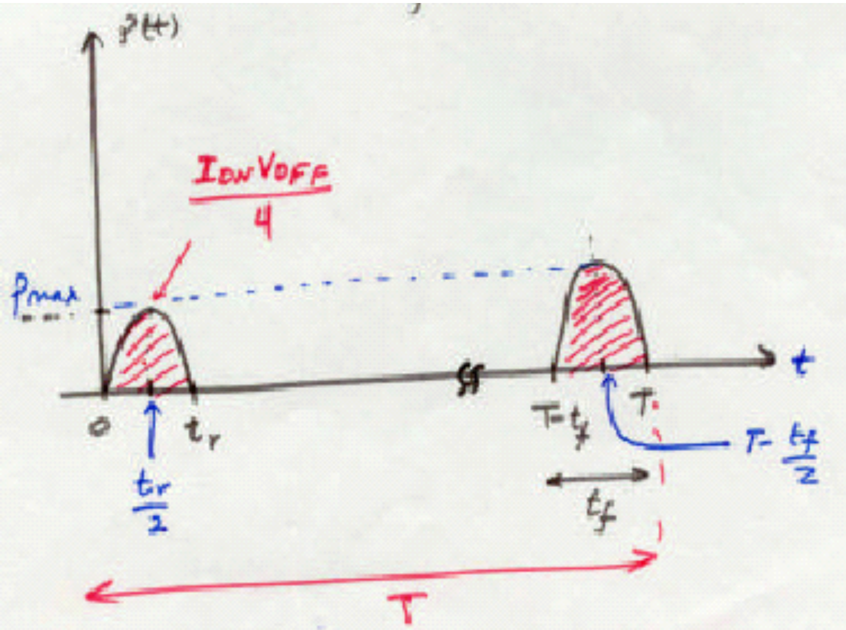
$$P_{ii}(t) = 0 \quad \text{(No conduction loss)}$$

iii) For $T - t_f < t \le T$

$$i_{sw}(t) = -\frac{I_{ON}}{t_f}(t-T)$$

$$V_{sw}(t) = \frac{V_{OFF}}{t_f}(t-(T-t_f))$$

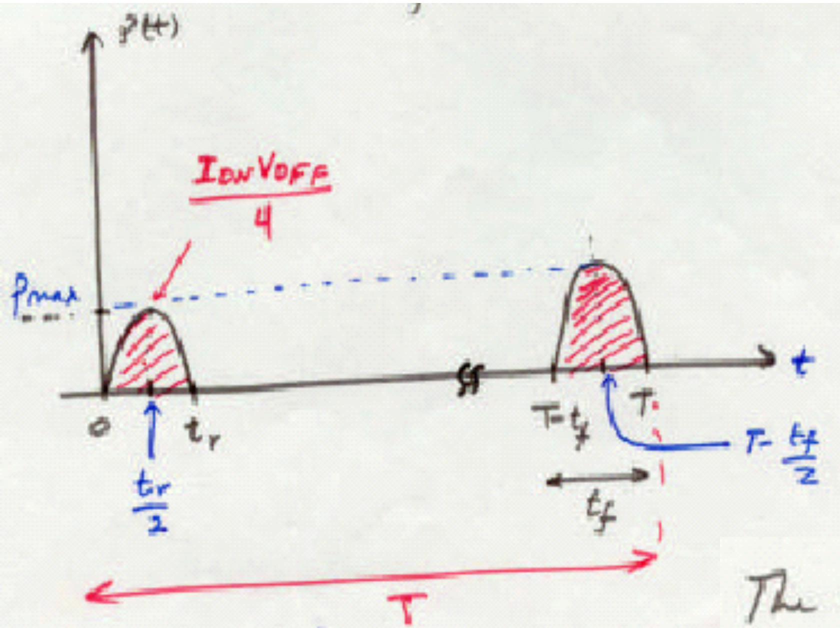
Another Switch Loss Example (Pmax)



$$p(t) = \begin{cases} -\dfrac{I_{ON} V_{OFF}}{t_r^2}(t-t_r)t & 0 < t \leq t_r \\ 0 & t_r < t \leq T-t_f \\ -\dfrac{I_{ON} V_{OFF}}{t_f^2}(t-(t-T))(t-T) & T-t_f < t \leq T \end{cases}$$

$$P_{tri}(t) = -\frac{I_{ON} V_{OFF}}{t_f^2}(t-(T-t_f))(t-T)$$

Another Switch Loss Example (Pmax)



The maximum power occurs at $t = t_{max}$,

$$\left.\frac{dP_c(t)}{dt}\right|_{t=t_{max}} = 0 = \left.\frac{-I_{ON}V_{OFF}}{t_r^2}(2t - t_r)\right|_{t=t_{max}} = 0$$

$$\therefore \quad 2t_{max} - t_r = 0$$

$$\therefore \quad t_{max} = \frac{t_r}{2}$$

Another Switch Loss Example (Pmax)

b) Determine the average power dissipated over one switching cycle,

$$P_{ave} = \frac{1}{T}\int_0^T p(t)\,dt$$

$$= \frac{1}{T}\left[\int_0^{t_r} P_i(t)\,dt + \int_{t_r}^{T-t_f} P_{ii}\,dt + \int_{T-t_f}^{T} P_{iii}\,dt\right]$$

$$= \frac{I_{ON} V_{OFF}}{T}\left(\frac{t_r - t_f}{6}\right)$$

$$= \frac{I_{ON} V_{OFF}}{6} \cdot (t_r - t_f) \cdot f$$

device power rating | device ~~switching~~ ~~speed~~ delay. | operating frequency

- **Should be tr+tf**