MOSFET Theory

ECE 320 Electronics I

Jake Glower - Lecture #22

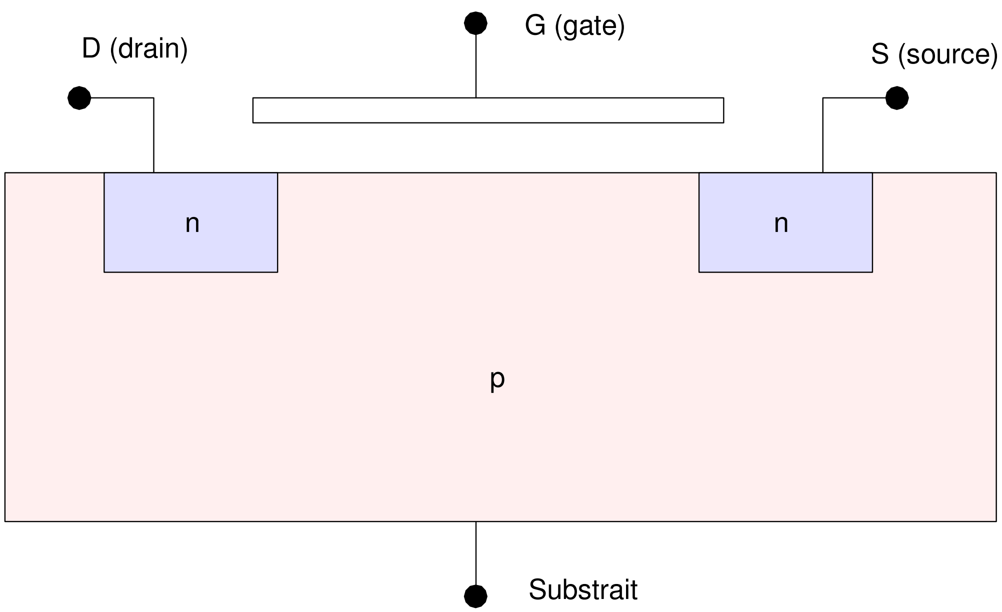
Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

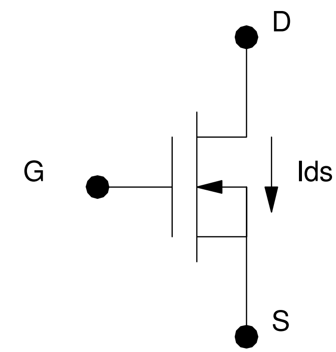
MOSFET Theory

Another type of 3-terminal device is called a MOSFET. In essence,

- A transistor is a current-controlled current source.
- A MOSFET is a voltage controlled resistor.

The design of an n-channel MOSFET is as follows:





Symbol

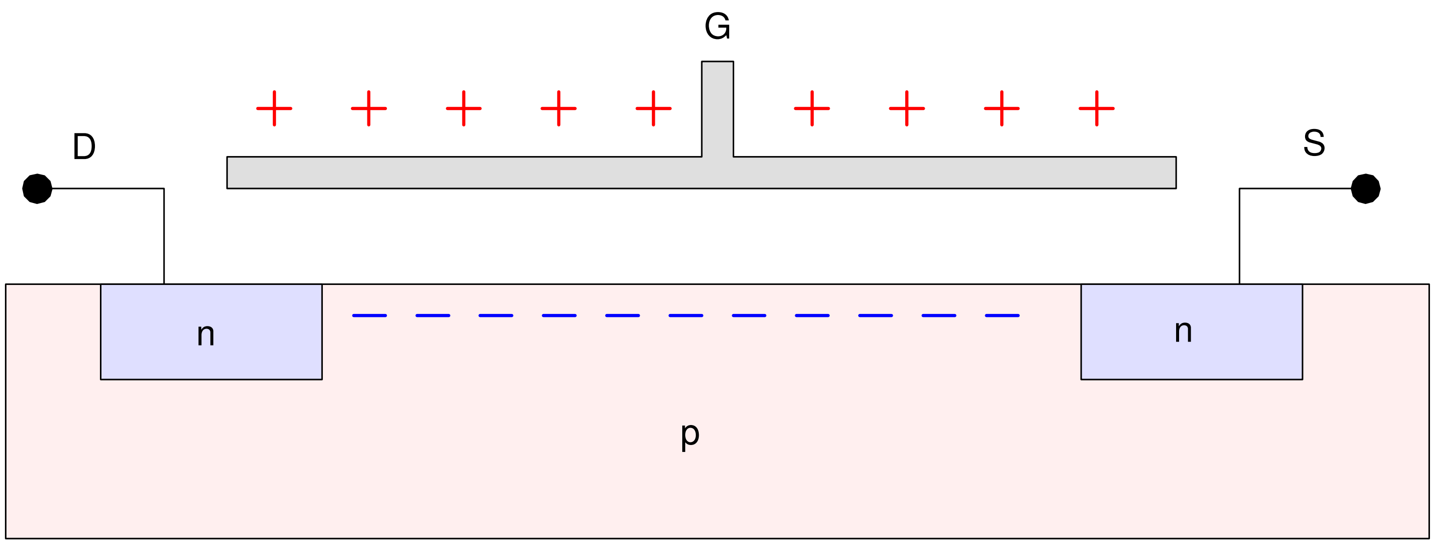
MOSFET Operation

Vgs = 0V

- Current = 0

Vgs = 5V

- Electrons attracted to the surface
- Creates an n-channel
- Higher Vgs makes n-channel bigger (lower R)



Three Modes of Operation

Off:

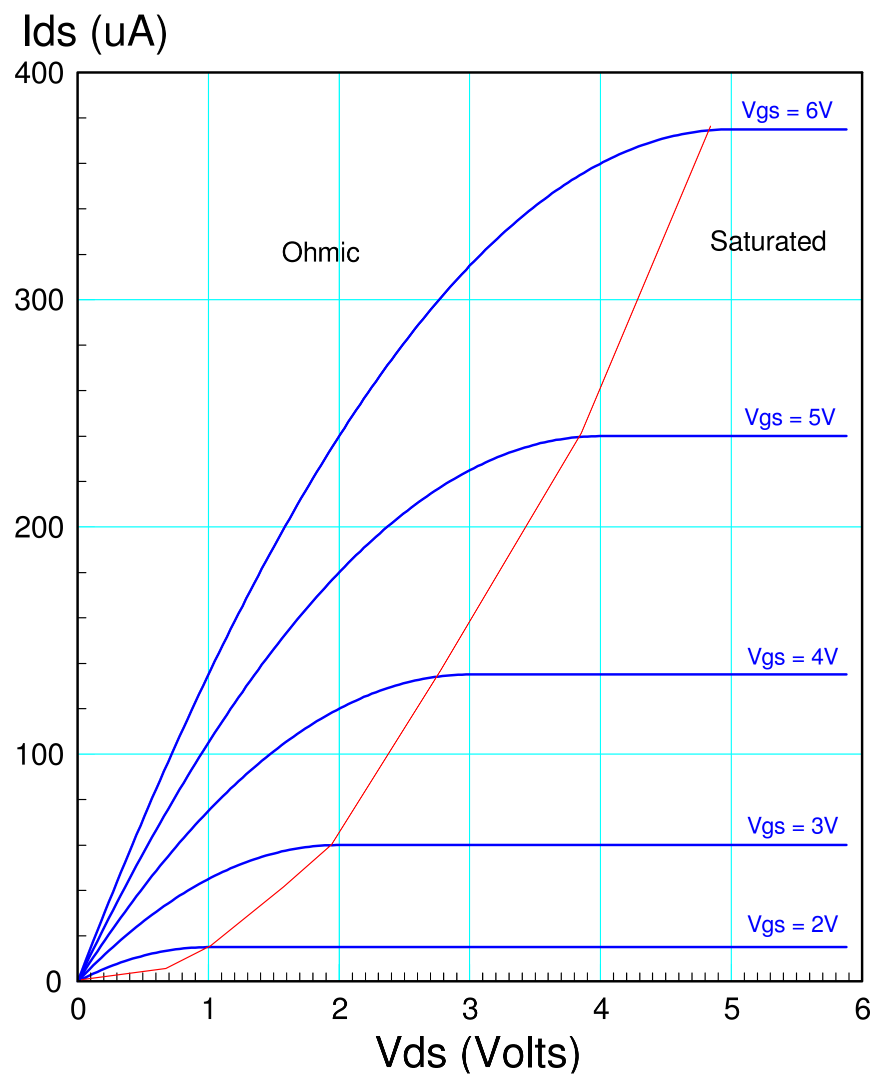
- Vgs < Vth
- No channel exists (current = 0)

Ohmic (Triode)

- Vth < Vgs < Vds + Vth
- Resistance = f(Vgs)
- $I_{ds} = k_n\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds}$

Saturated

- Ran out of charge carriers
- Current = f(Vgs)
- $I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$

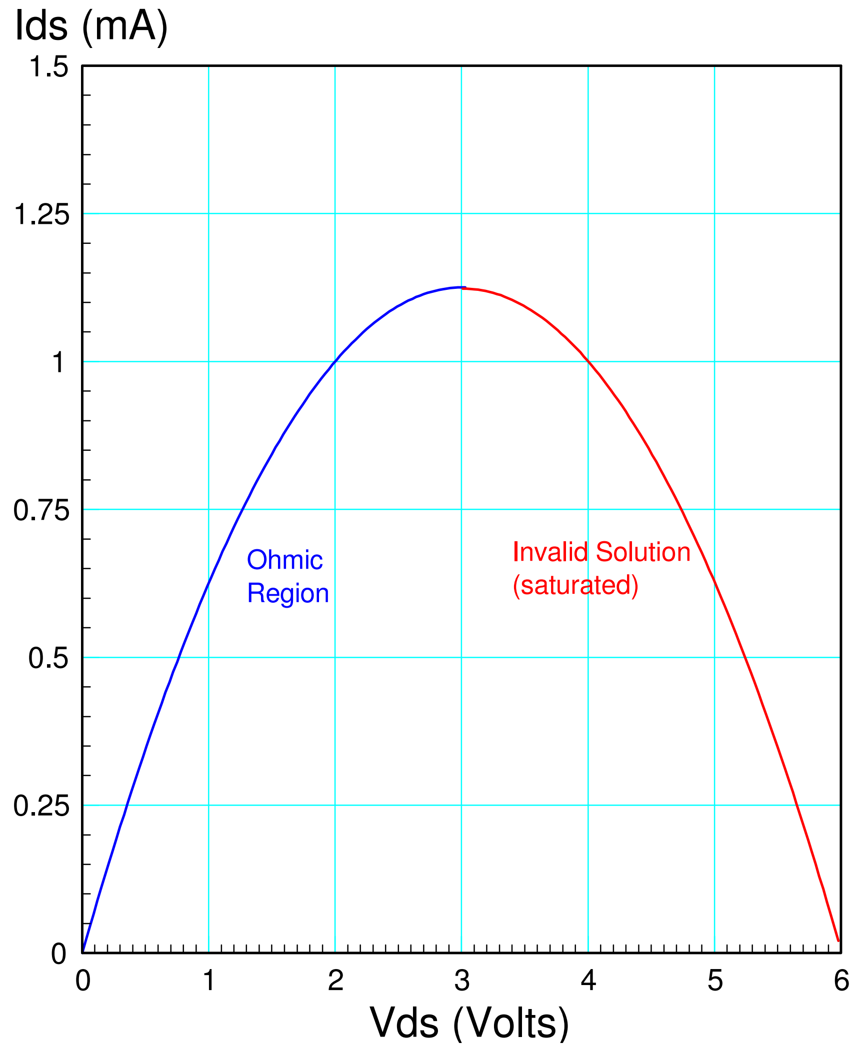


Example: Plot the VI characteristic for a MOSFET with

- $V_{th} = 1V$
- $V_{GS} = 4V$
- $k_n = 250\mu A/V^2$

Ohmic Region:

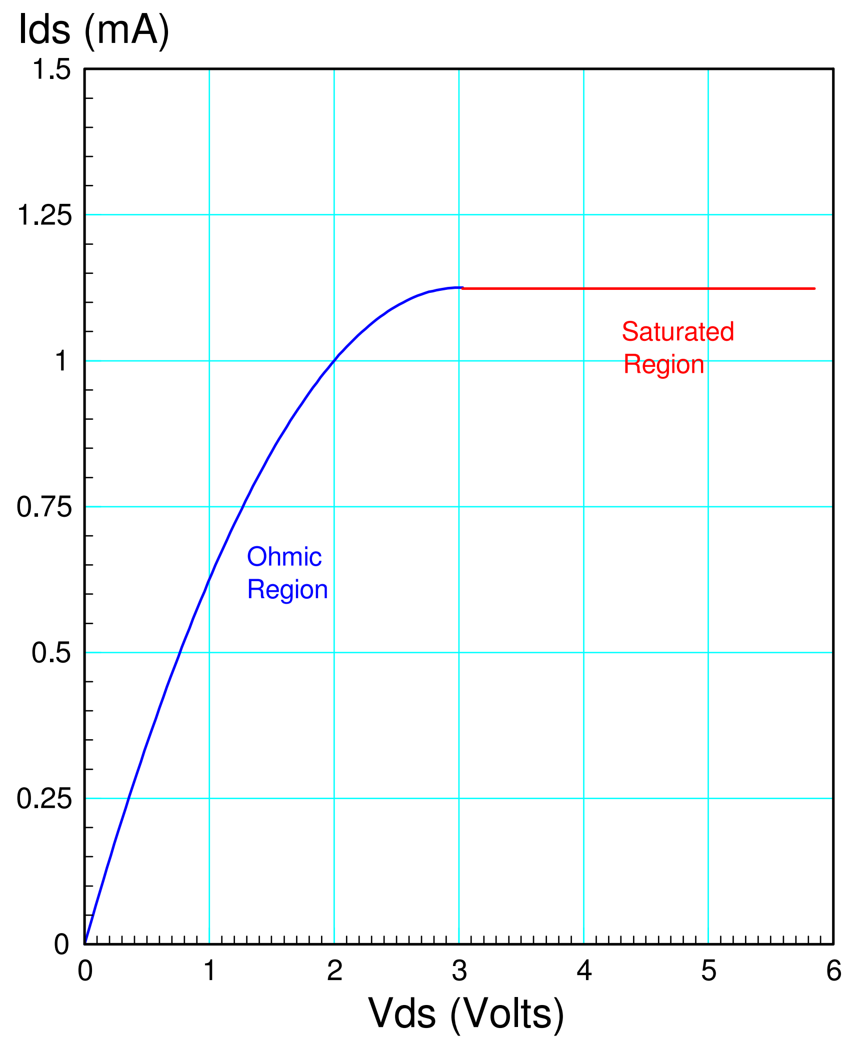
```
Vgs = 4;

Vds = [0:0.03:6]';
Vth = 1;
Kn = 250e-6;

% Ohmic

Ids = Kn*(Vgs - Vth - Vds/2).*Vds;

plot(Vds, Ids*1000)
xlabel('Vds (V)');
ylabel('Ids (mA)')
```



Saturation (Pinch-Off) Region

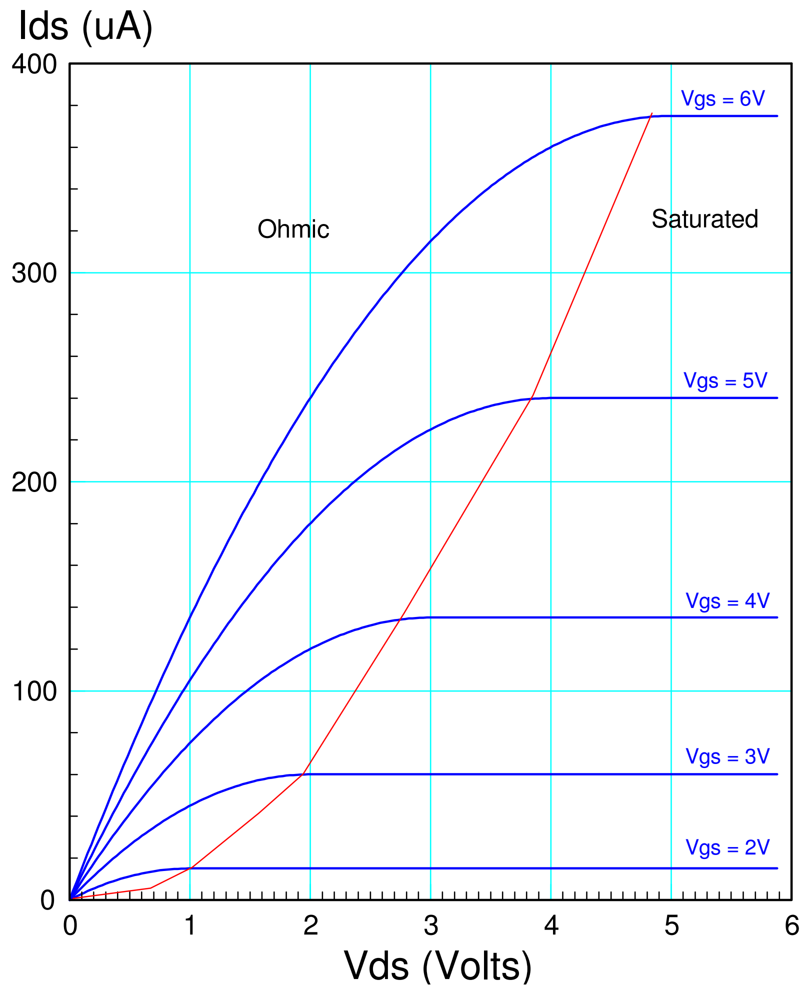
When the slope becomes negative, Ids = constant

- Ran out of charge carriers
- $V_{DS} > V_{GS} - V_{TN}$
- $I_{DS} = \frac{K_n}{2}(V_{GS} - V_{TN})^2$



V/I Relationship for a MOSFET

```
Vth = 1;
Kn = 0.03;
Vds = [0:0.03:5.9]' + 1e-6;
DATA = [];

for i=1:5
   Vgs = Vth + i;
% Ohmic
   Ids1 = Kn*(Vgs - Vth - Vds/2).*Vds;
   Ids1 = Ids1 .* (Vgs - Vth > Vds);
% Saturated
   Ids2 = Kn/2 * (Vgs - Vth).^2;
   Ids2 = Ids2 .* (Vds > Vgs - Vth);
   Ids = Ids1 + Ids2;
   DATA = [DATA, Ids];
   end
plot(Vds, DATA);
xlabel('Vds (V)');
ylabel('Ids (mA)')
```



Example 1: Determine Kn and Vth

Vth = 2V

- Turns on at something less than 3V

k_n:

- Ohmic region (A)

$$I_{ds} = k_n\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds}$$

$$2mA = k_n\left(7V - 2V - \frac{2V}{2}\right)2V$$

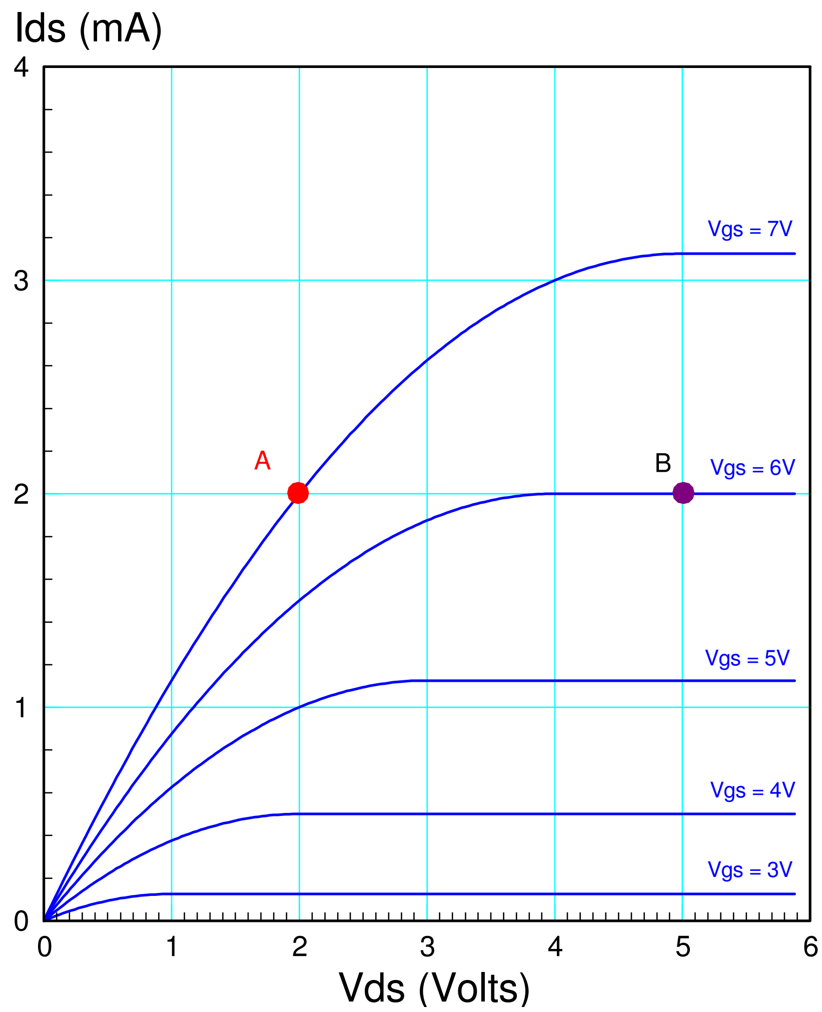
$$k_n = 0.25mA/V^2$$

- Saturated Region (B)

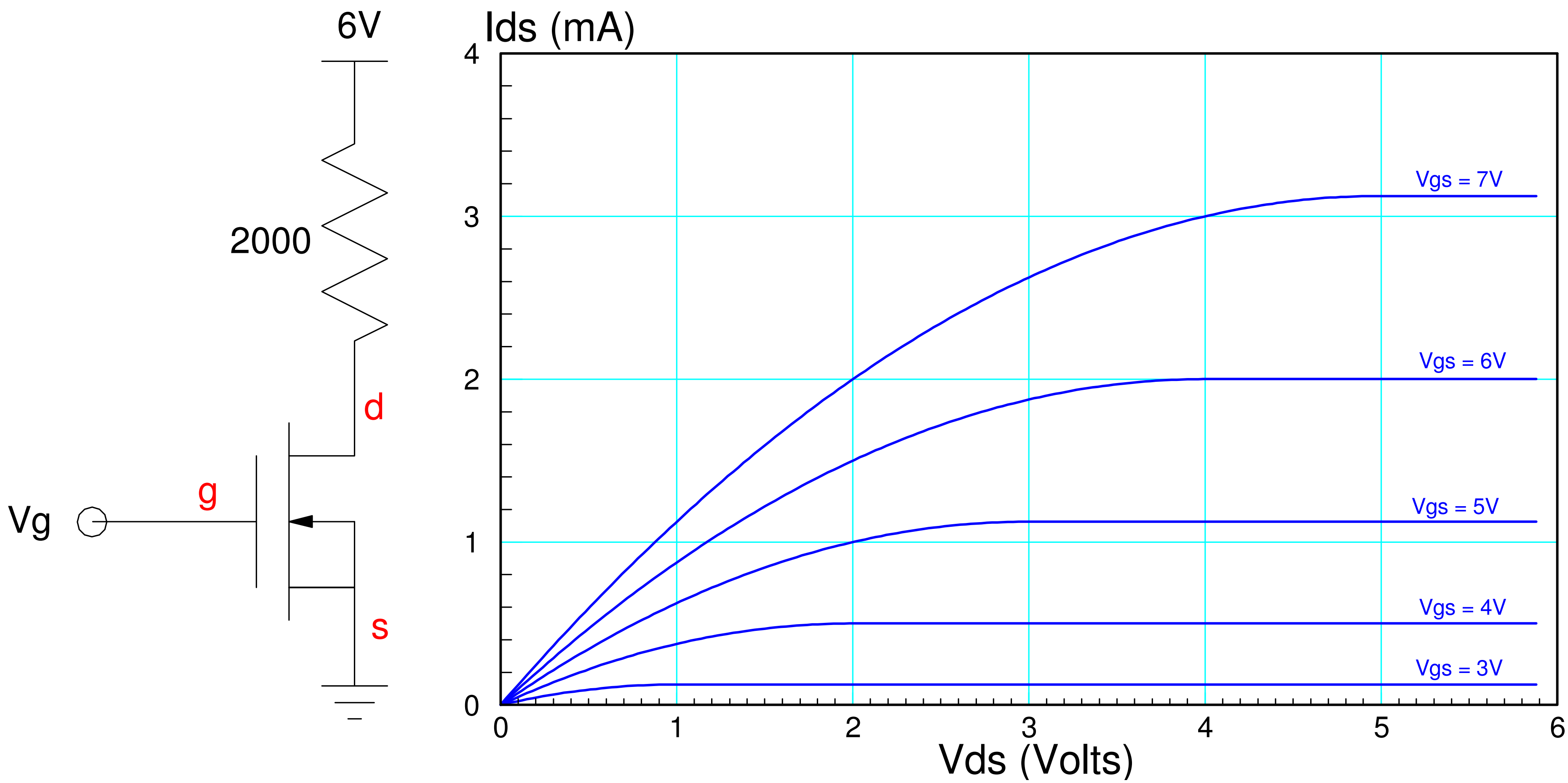
$$I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

$$2mA = \frac{k_n}{2}(6V - 2V)^2$$

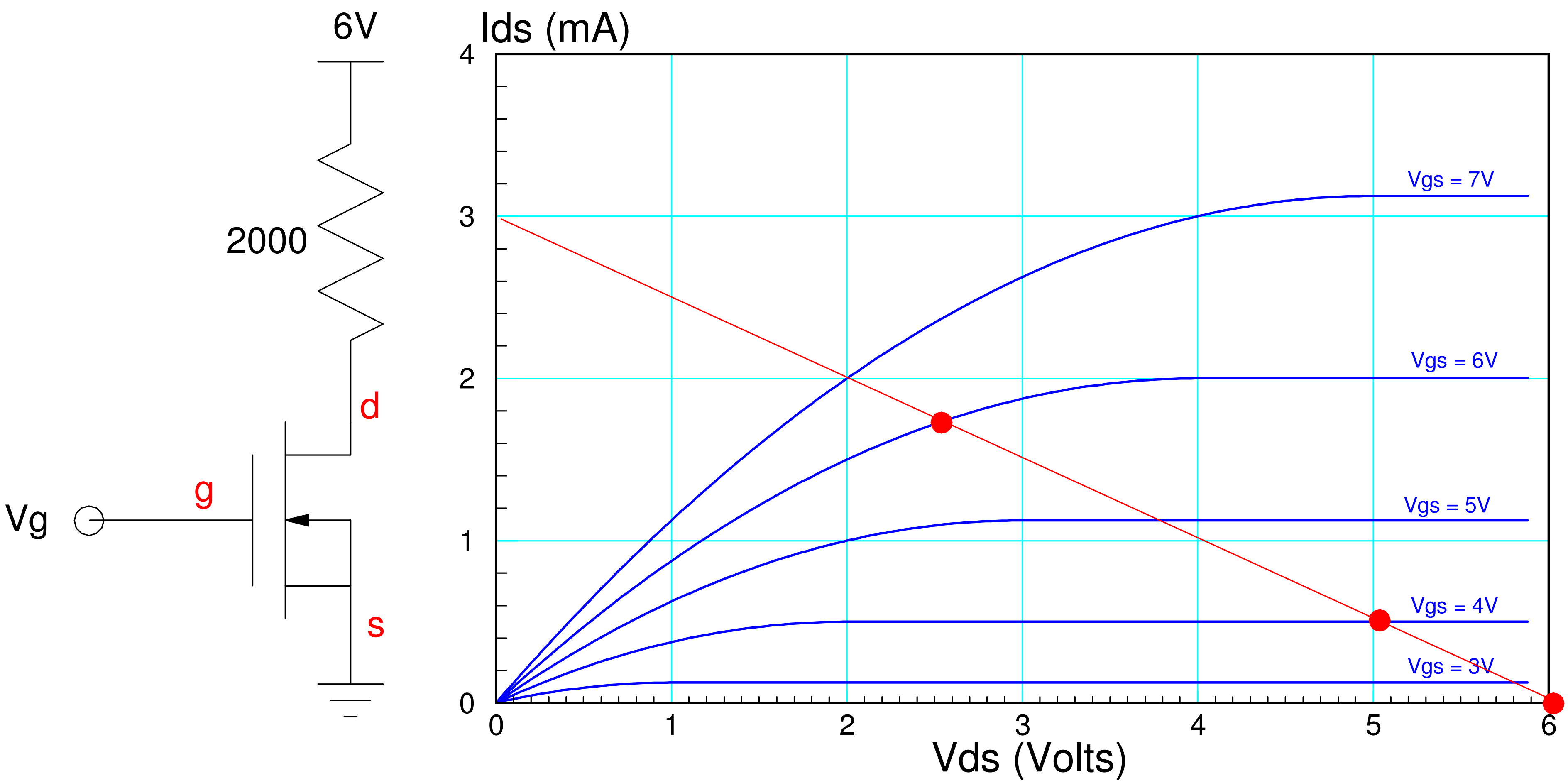
$$k_n = 0.25mA/V^2$$



Example 2: Determine (Vds, Ids) for Vg = { 0V, 4V, 6V }

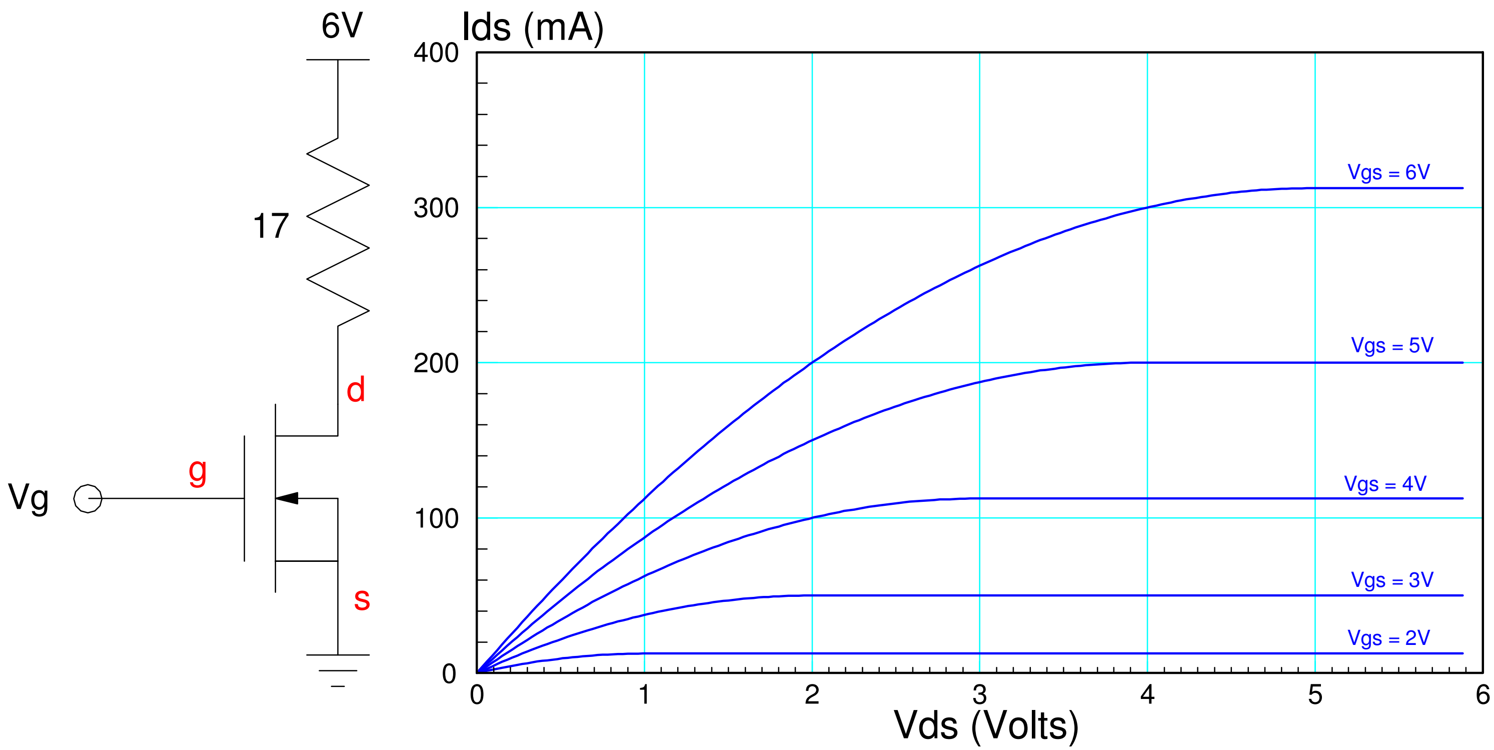


Solution (graphical): Draw the load line



Handout

- 1) Label the off / Saturated / Ohmic regions
- 2) Determine kn. Assume Vtn = 1.0V
- 3) Draw the load line for the following circuit
- 4) Determine the Q-point when Vg = { 0V, 4V, 6V }



Numerical Solution: Vg = 4V

Assume Saturated

$$I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

$$I_{ds} = \left(\frac{0.25\frac{mA}{V^2}}{2}\right)(4V - 1V)^2$$

$$I_{ds} = 1.125mA$$

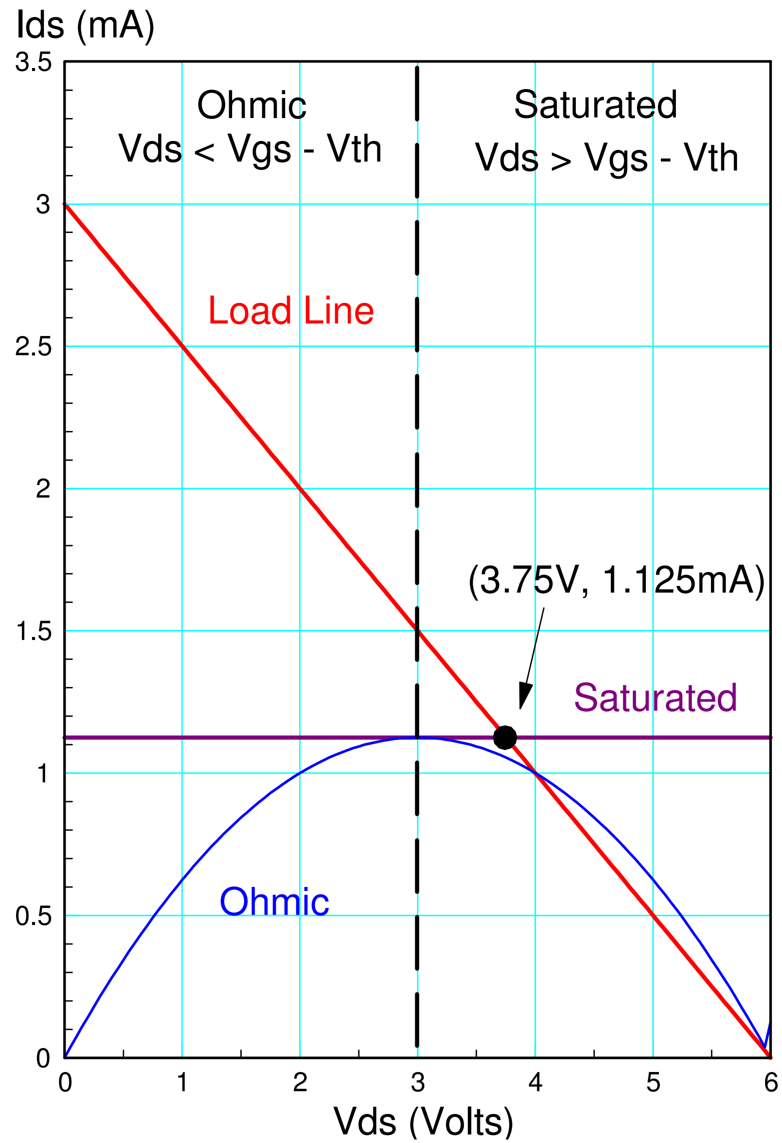
$$V_{ds} = 6V - 2000\Omega \cdot I_{ds}$$

$$V_{ds} = 3.75V$$

Check

$$V_{ds} > V_{gs} - V_{th}$$

$$3.75V > 4V - 1V$$



Numerical Solution: Vg = 4V

Assume Ohmic

$$I_{ds} = k_n\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds}$$

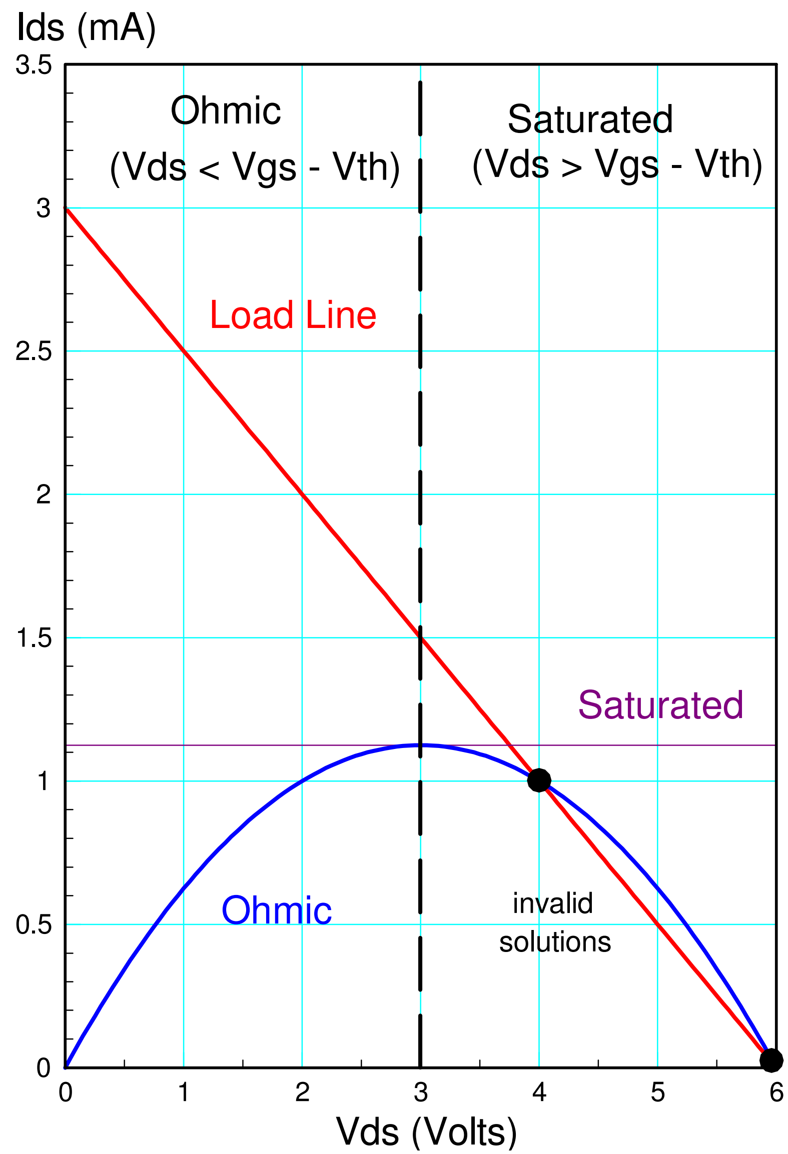
$$I_{ds} = \left(0.25\frac{mA}{V^2}\right)\left(4V - 1V - \frac{V_{ds}}{2}\right)V_{ds}$$

$$V_{ds} + 2000I_{ds} = 6V$$

Solution:

Vds > 3V (invalid solution)

often results in no solution



Numerical Solution: Vgs = 6V

Assume Saturated

$$I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

$$I_{ds} = \frac{0.25\frac{mA}{V^2}}{2}(6V - 1V)^2$$

$$I_{ds} = 3.125V$$

$$V_{ds} = 6V - 2k\Omega \cdot I_{ds}$$

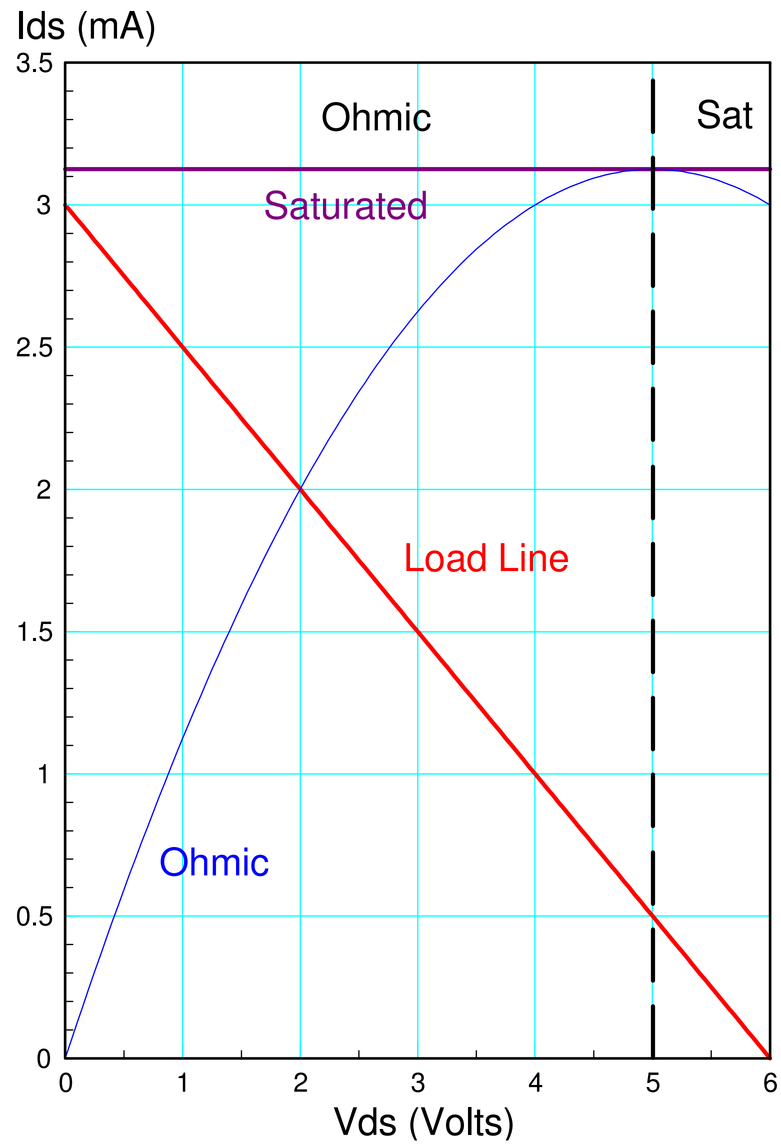
$$V_{ds} = 0.25V$$

Check

negative Vds isn't possible

it's not saturated

$$V_{ds} > V_{gs} - V_{th}$$



Numerical Solution: Vgs = 6V

Assume Ohmic

$$I_{ds} = k_n\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds}$$

$$I_{ds} = \left(0.25\frac{mA}{V^2}\right)\left(6V - 1V - \frac{V_{ds}}{2}\right)V_{ds}$$

$$6V = V_{ds} + 2000I_{ds}$$

Solution (solved numerically)

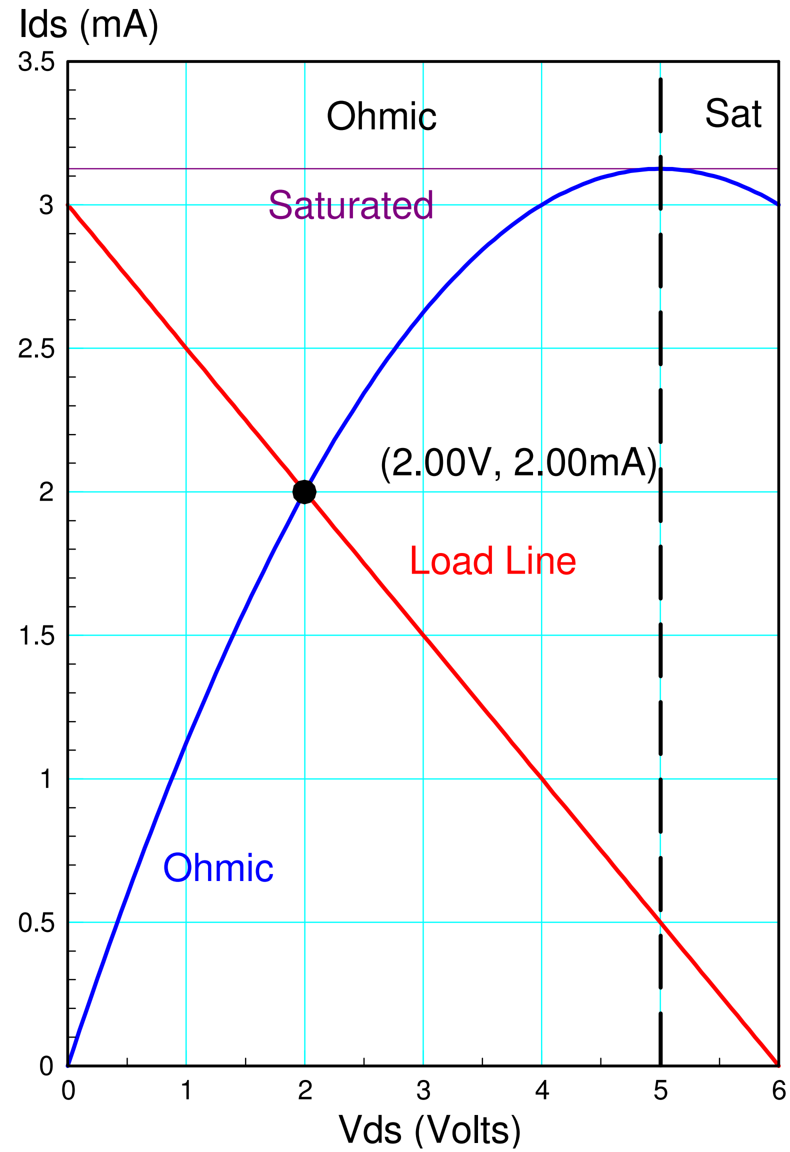
Vds = 2.000V

Ids = 2.000mA

Check

$$V_{ds} < V_{gs} - V_{th}$$

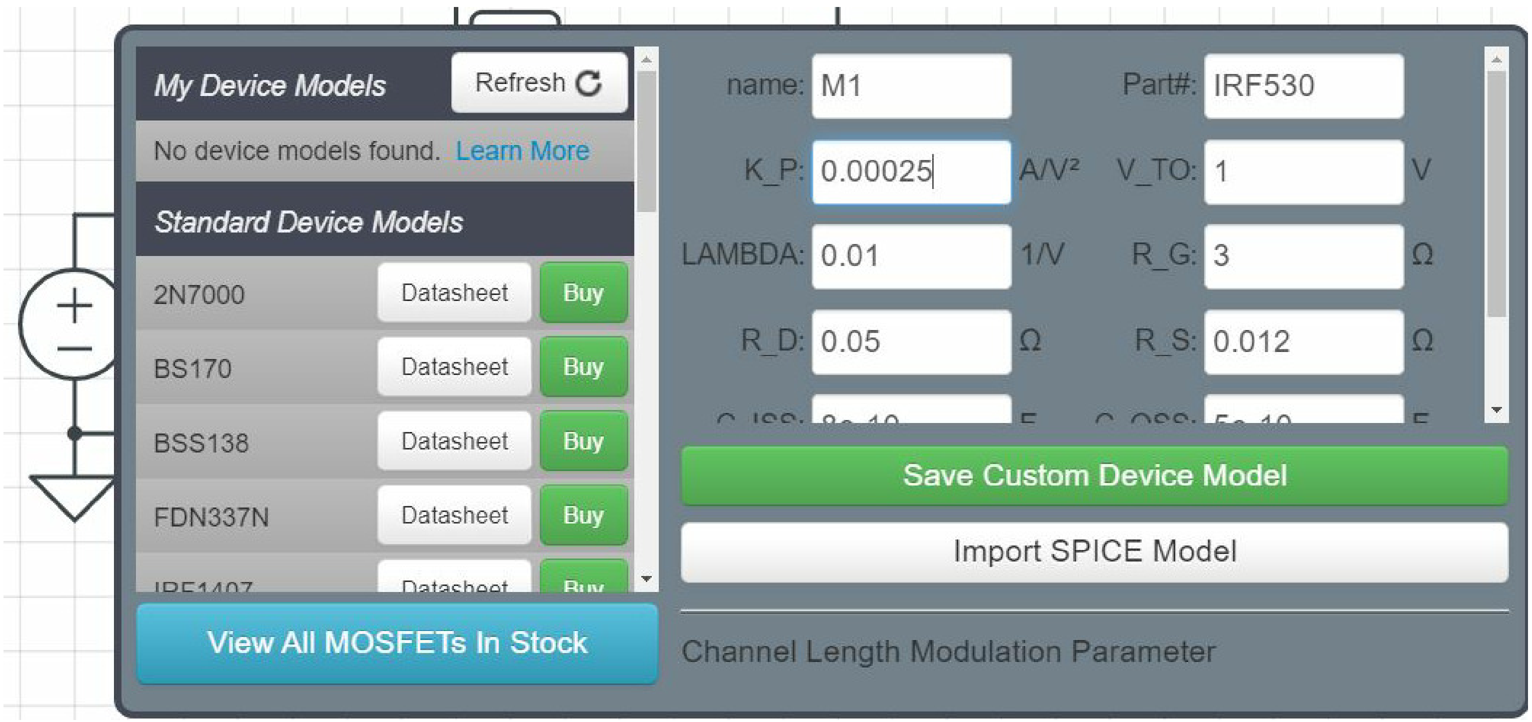
$$2V < 6V - 5V$$



Solution: CircuitLab

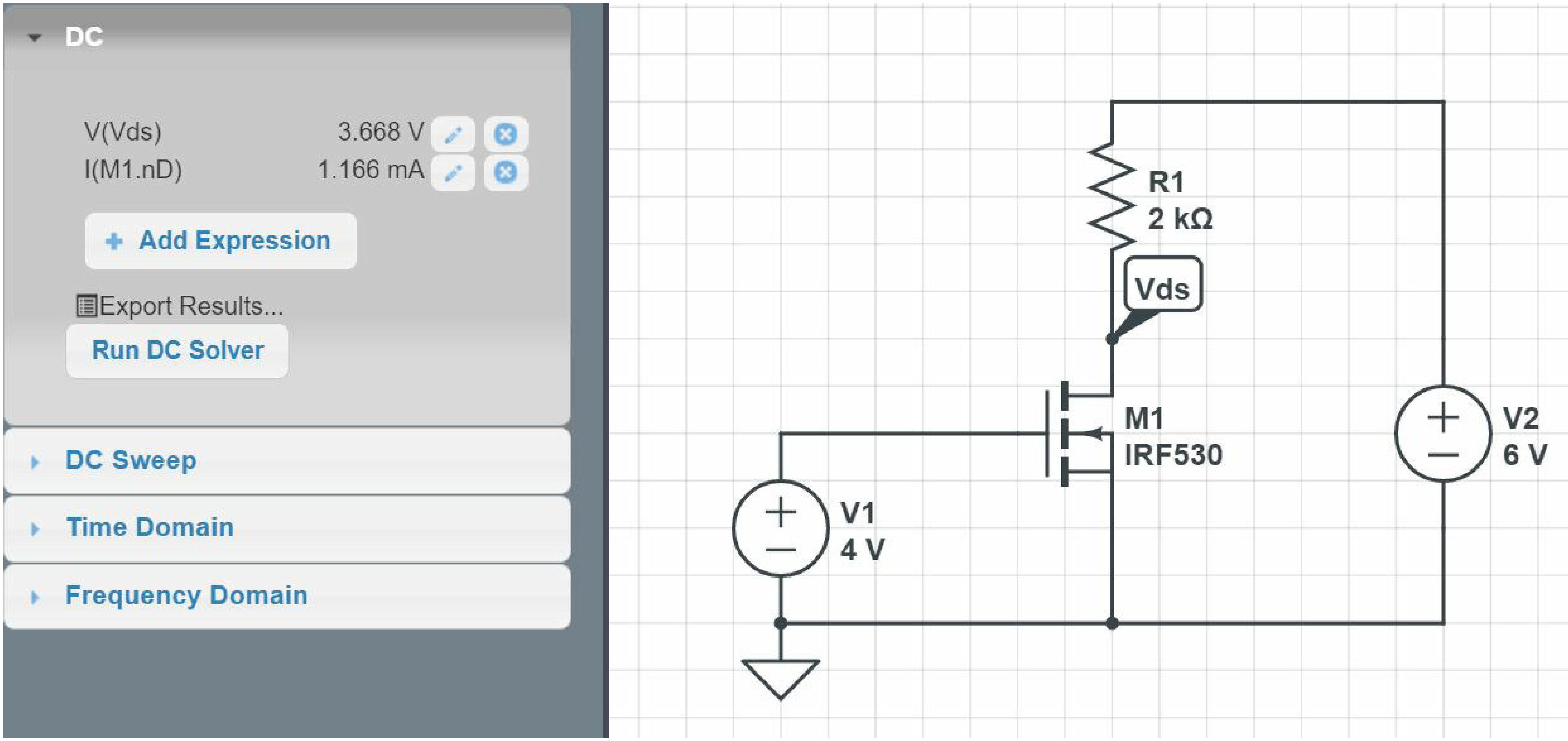
Change the MOSFET properties to match

- kn = 0.25 mA / V2
- Vth = 1V



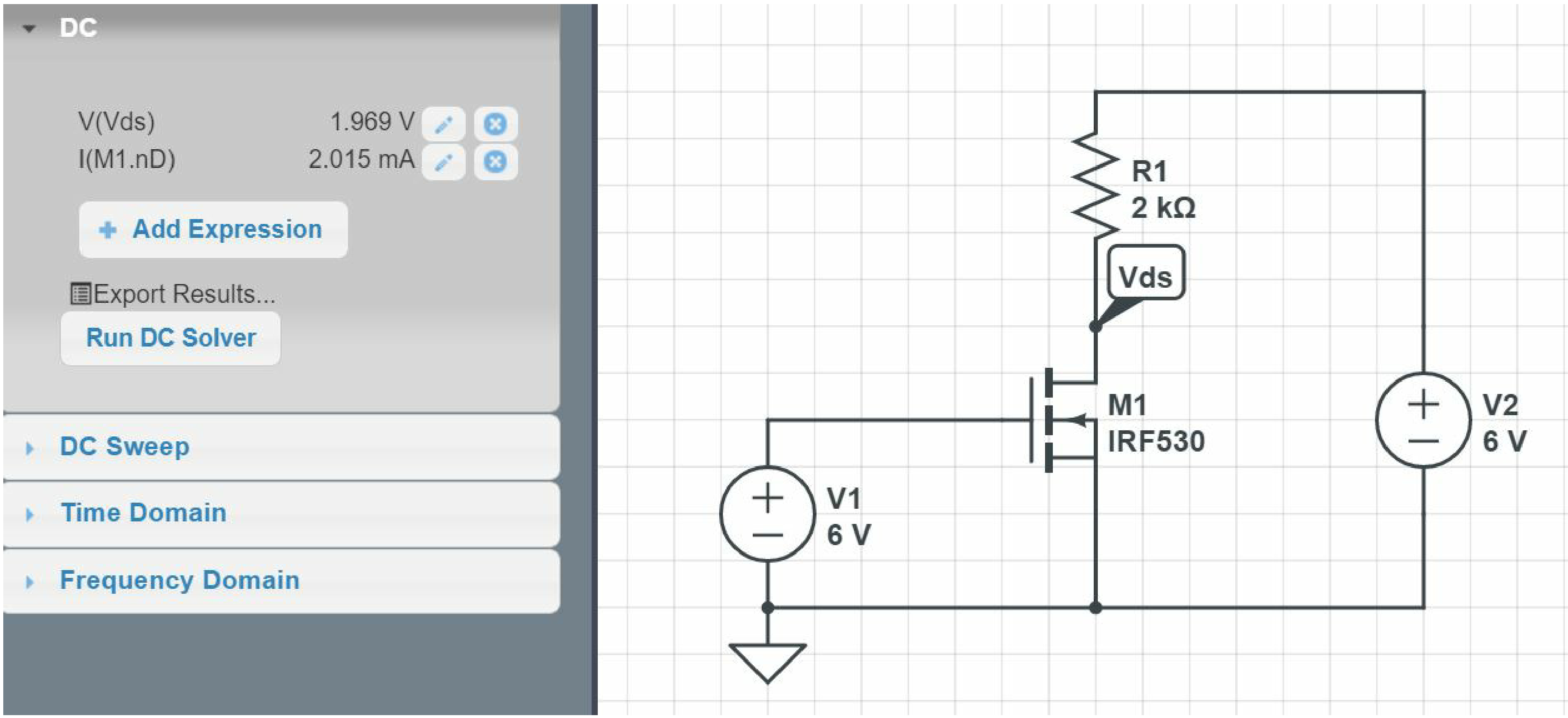
Solution: CircuitLab

- (3.75V, 1.125mA) calculated



Solution: CircuitLab

- (2.00V, 2.00mA) calculated



Example 3: Determine the Q-point (Vds, Ids) when

- $V_g = 5V$
- $V_g = 6.2V$

Assume

- $k_n = 0.6\ A/V^2$
- $V_{th} = 4V$

Ohmic Region (option #1 for first equation)

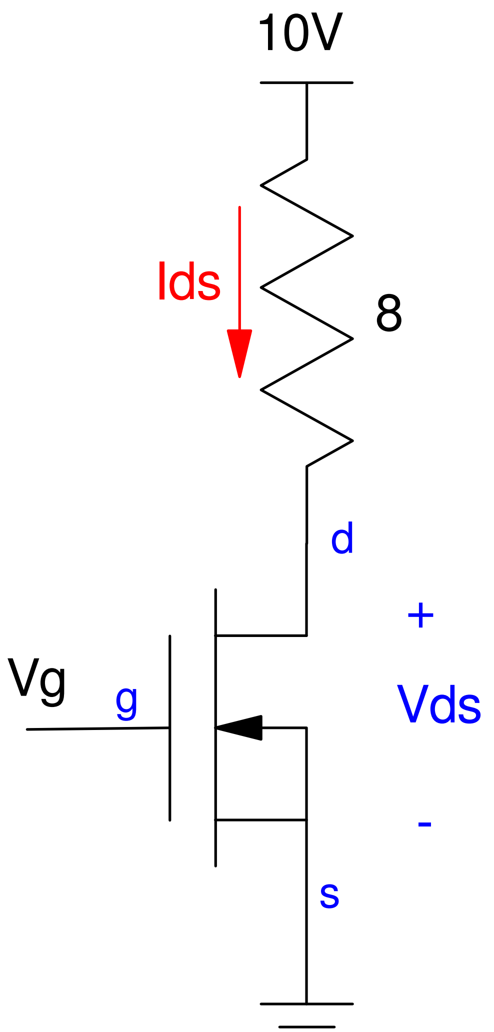
$$I_{ds} = k_n\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds}$$

Saturated Region (option #2 for first equation)

$$I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

Load Line (second equation)

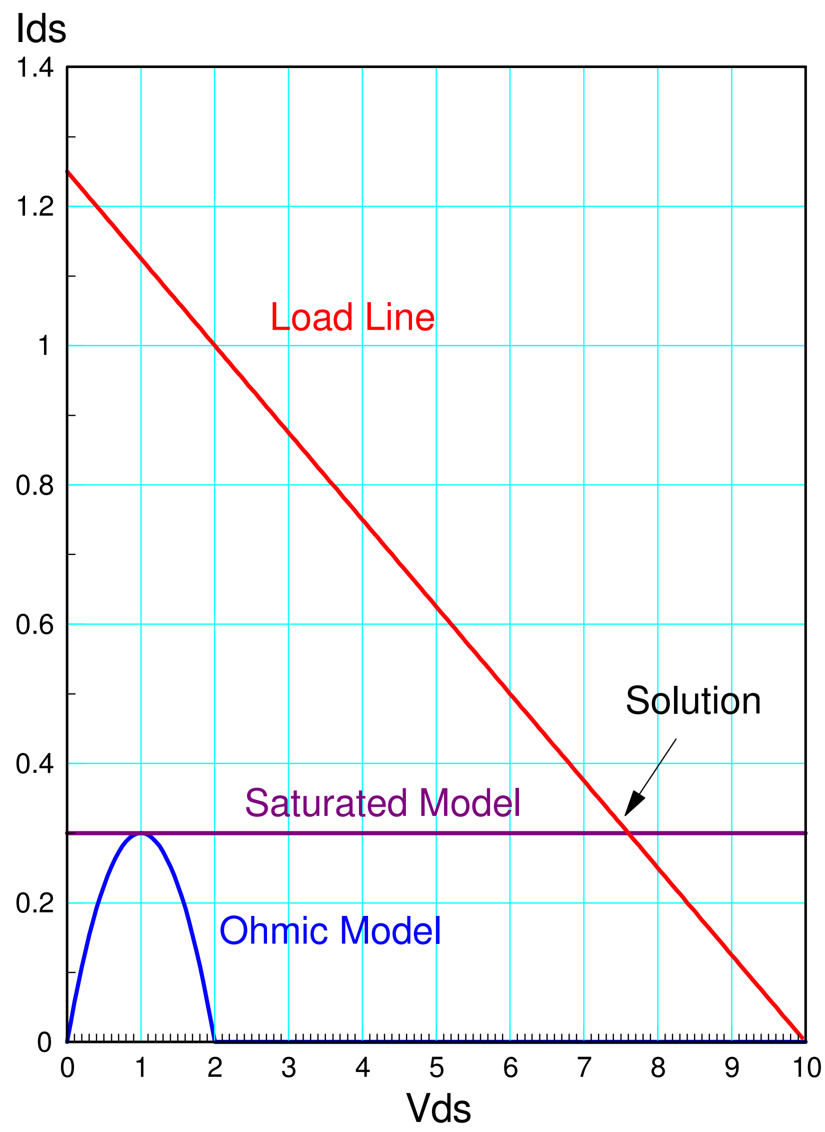
$$V_{ds} + 8I_{ds} = 20$$



Case 1: Vg = 5V

Matlab Code

```
kn = 0.6;
Vth = 4;
Vg = 5;
Vds = [0:0.05:10]';
I1 = kn*(Vg - Vth - Vds/2).*Vds;
I2 = 0*I1 + max(I1);
I3 = ( 10 - Vds) / 8;
plot(Vds,I1,Vds,I2,Vds,I3)
ylim([0,1.5])
```



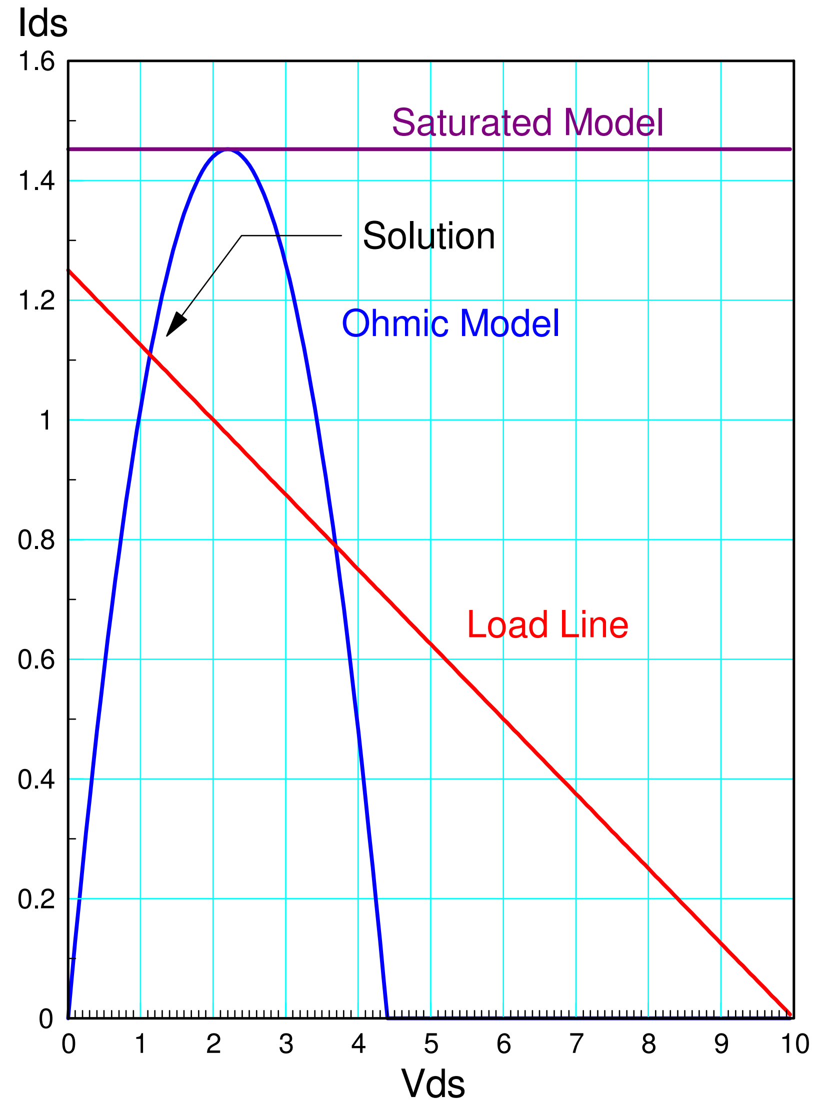
You're in the saturated region

- Ohmic model has no solution
- Saturated model works

Case 2: Vg = 6.2V

Matlab Code

```
kn = 0.6;
Vth = 4;
Vg = 6.2;
Vds = [0:0.05:10]';
I1 = kn*(Vg - Vth - Vds/2).*Vds;
I2 = 0*I1 + max(I1);
I3 = ( 10 - Vds) / 8;
plot(Vds,I1,Vds,I2,Vds,I3)
ylim([0,1.5])
```



You're in the ohmic region

- Saturated model results in negative Vds
- Ohmic model gives two solutions
- The solution close to Vds = 0 is the correct one

Summary

MOSFETs are voltage controlled resistors

- n-channel MOSFET (similar to NPN transistors)
- p-channel MOSFET (similar to PNP transistors)

MOSFETs have three modes of operation

- Off

$$I_{ds} = 0$$

- Saturated

$$I_d = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

- Ohmic

$$I_d = k_n\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds}$$