Lecture-43

EE5325 Power Management Integrated Circuits

Dr. Qadeer Ahmad Khan

Integrated Circuits and Systems Group
Department of Electrical Engineering
IIT Madras

Current Sensing

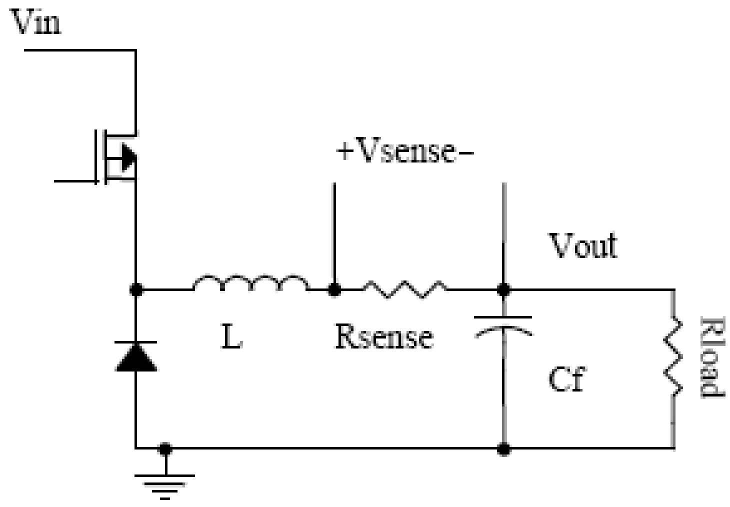
- **Current sensing in a dc-dc converter is used mainly for following purposes**
  1. Limit the inductor peak current from getting saturated (Over Current Protection – OCP)
  2. Use the inductor current information in current mode control
  3. Limit average power stage current within the maximum rated specification (Over Current Protection – OCP)
  4. Regulate the average output/load current in case of current regulator (battery charger, LED drivers etc.)
  5. Transition between PWM and PFM mode based on load current
- **Current sensing can be based on:**
  - **Peak current sensing:** used for 1 and 2
  - **Average current sensing:** used for 3-5
- **Information obtained from peak current sensing can also be used to calculate the average current but not vice versa**

Current Sensing Methods

- Sense resistor based current sensing
- MOSFET R_{DS_ON} based current sensing
- MOSFET V_{DS} based current sensing
- Observer (integrator) based current sensing
- RC filter based current sensing
- SenseFET based current sensing
- Transformer based current sensing

Sense Resistor

- Uses a Sense Resistor in series with the inductor
- If the value of the resistor is known, the current flowing through the inductor is determined by sensing the voltage across it.
- The technique is simple but not very power efficient due to losses incurred in series Rsense
- Assuming Rsense=100mOhm, for an output voltage of 1.8V and load current of 1A, loss due to Rsense could be ~5%

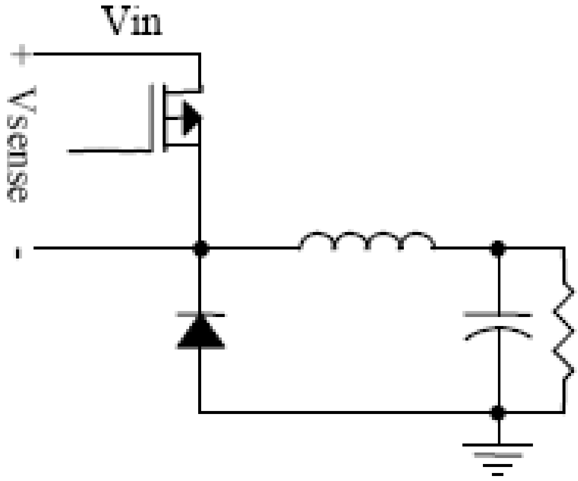


MOSFET RDS Current Sensing

- MOSFETs act as resistors when they are "ON"
- The equivalent resistance of the device is:
- R_{DS} in this case should be known ; VDS is measured.
- Accuracy is not good due to variation in RDS_ON across process, voltage and temperature

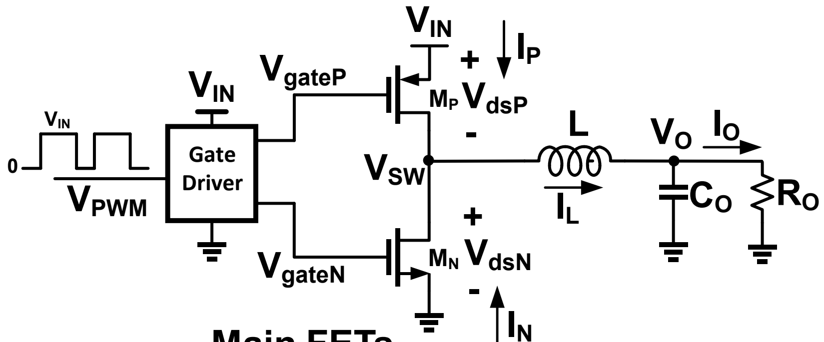
$$I_D = \mu \cdot C_{OX} \cdot \frac{W}{L} \cdot (V_{GS} - V_T) \cdot V_{DS} \quad ; \quad for : |V_{DS} << (V_{GS} - V_T)|$$

$$R_{DS} = \frac{L}{W \cdot \mu \cdot C_{OX} \cdot (V_{GS} - V_T)}$$

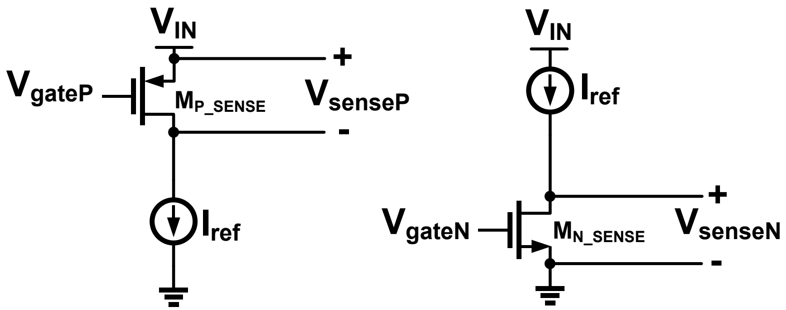


MOSFET VDS Current Sensing

- Based on sensing V_{DS} of main FET and sense FET
- Assumes main FET and sense FET have same variations across PVT
- V_{DS} of sense FET is generated by forcing a fixed bias current Iref
- Requires post processing (division) to get the final current value



Main FETs



Sense FETs

from main PFET (M_P)

$$I_P = \frac{V_{dsP}}{R_{dsP}} \qquad (1)$$

from sense PFET (M_{P_SENSE})

$$I_{REF} = \frac{V_{senseP}}{R_{ds\_senseP}} \qquad (2)$$

divide (1) and (2), we get :

$$\frac{I_p}{I_{ref}} = \frac{V_{dsP}}{V_{senseP}} \cdot \frac{R_{ds\_senseP}}{R_{ds\_P}}$$

$$or \quad I_p = I_{ref} \cdot \frac{V_{dsP}}{V_{senseP}} \cdot \frac{R_{ds\_senseP}}{R_{ds\_P}} \qquad (3)$$

if width ratio of main FET to sense FET is N :

$$R_{ds\_senseP} = N \cdot R_{ds\_P}$$

substituting in (3), we get :

$$\boxed{I_p = N \cdot I_{ref} \cdot \frac{V_{dsP}}{V_{senseP}}}$$

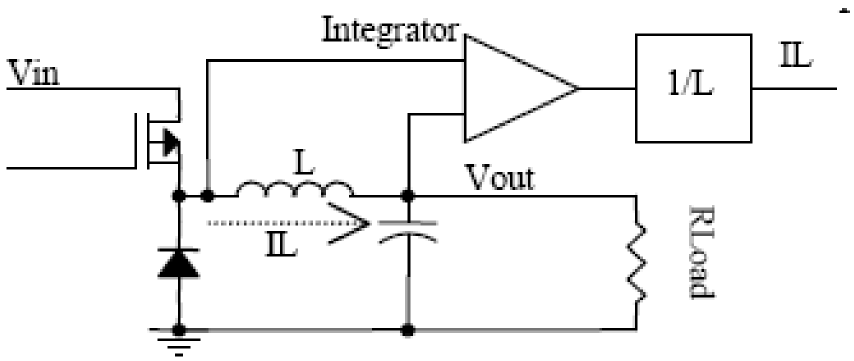
simlarly :

$$\boxed{I_N = N \cdot I_{ref} \cdot \frac{V_{dsN}}{V_{senseN}}}$$

Observer Based Sensing

- This method uses the Inductor voltage to measure the Inductor current
- Inductor current can be calculated by integrating the voltage over time
- Integrator time constant should match inductor value
- Difficult to track the variation in inductors

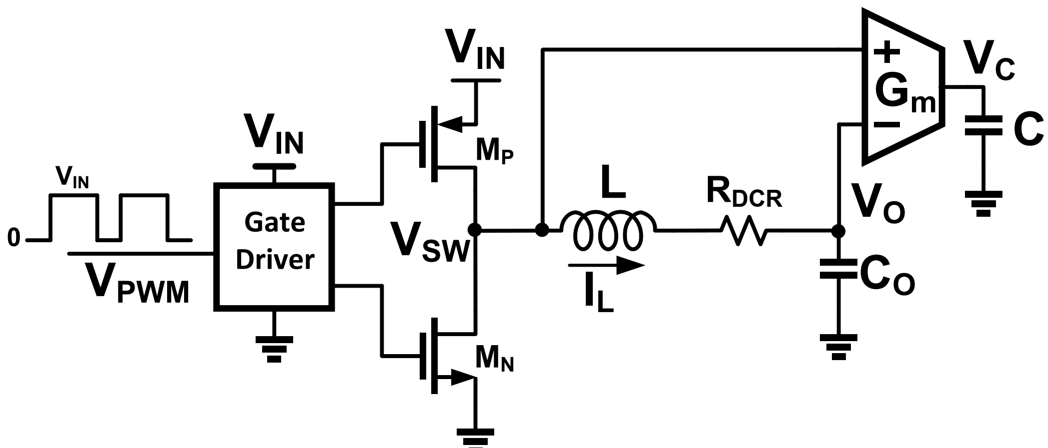
$$v_L = L\frac{di}{dt} \Rightarrow i_L = \frac{1}{L}\int v_L dt$$



Issues With Observer Based Sensing

- Difficult to track the variations in inductor
- Works only with zero loss across the inductor (i.e. R_{DCR}=0 or I_{LOAD}=0)
- Can be used to determine the ripple current information by resetting the integrator every cycle

Inductor: $I_L = \frac{1}{L}\int V_L\, dt$ **Gm-C:** $V_C = \frac{G_m}{C}\int V_L\, dt$



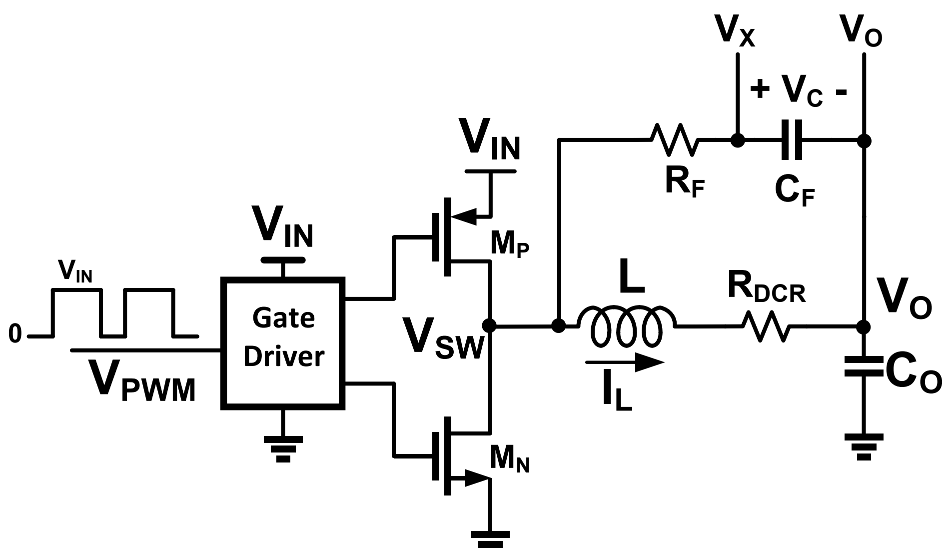
if $L = \frac{C}{G_m}$

then $V_C = I_L$

Under no load condition

RC Filter Based Sensing

- RC low pass filter is connected in parallel with inductor (same as used in current mode hysteretic)
- Average voltage across C_F is same as voltage drop across R_{DCR} → provides dc current sensing. R_{DCR} must be known to find the sensed dc current.
- If $R_F C_F$=k.L then ripple voltage across C_F provides ripple current sensing. K should be chosen such that $R_F C_F$>>T_{SW} (usually > 5 for good accuracy)



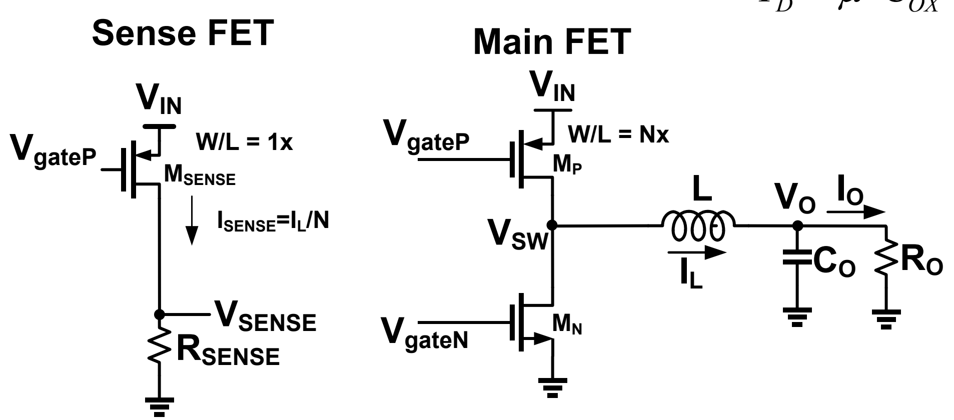
$$I_L(dc) = \frac{V_C(dc)}{R_{DCR}}$$

$$\Delta I_L = \mathrm{k} \cdot \Delta V_C$$

SenseFETs Based Current Sensing

- **Most commonly used method for current sensing**
- **The idea is to build a current sensing FET in parallel with the power MOSFET (Current Mirror).**
- **The effective width (W) of the sense MOSFET (SenseFET) is significantly smaller than the power FET, and therefore sensed current is scaled down version of the actual load current:**

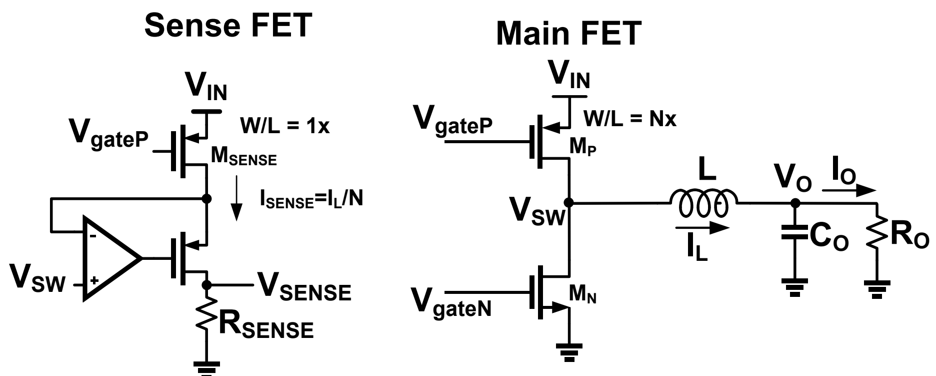
$$I_D = \mu \cdot C_{OX} \cdot \frac{W}{L} \cdot (V_{GS} - V_T) \cdot V_{DS}$$



- **The width (W) of the Power MOSFET is X1000-10000 times the width of SENSEFET to reduce the power consumption.**

Modified SenseFETs Based Current Sensing

- The Op-amp is used to force VDS of mainFET and SenseFET to be equal
- As width ratio of main MOSFET to SENSEFET increases, the accuracy of the circuit decreases. Bigger SENSEFET improves accuracy but will consume higher current due to increase in sense current (tradeoff between accuracy and quiescent current)
- Requires high gain-bandwidth (GBW) amplifier for sensing
- Advantages
  - Lossless (sensor current is small)
  - Can be easily integrated on-chip
  - Relatively good accuracy
- Sources of Error
  - Op-amp offset and limited bandwidth
  - Mismatch between main FET and sense FET (smaller sense FET has more error)
  - Variation in Rsense



Current Transformers

- **The use of this technique is common in high power systems.**
- **The idea is to sense a fraction of the high Inductor current by using the mutual inductor properties of a transformer.**

- **Main Disadvantages:**
  - **Increased cost and size and non-integrablity.**
  - **The transformer also cannot transfer the DC portion of current, which make this method inappropriate for over current protection.**

Comparison of Current-Sensing Techniques

Current Sensing Method	Advantages	Disadvantages
Series Sense Resistor	Good accuracy	Increases conduction loss
MOSFET R_{DS} Sensing	Lossless	Low accuracy as R_{DS} is not constant
MOSFET V_{DS} Sensing	Lossless, relatively better accuracy compared to R_{DS}	Accuracy depends upon matching between transistors, requires post processing to get the final current value
Current Observer	Lossless	Works with known L, does not work under load
RC Filter	Lossless, occupies large on-chip area	Works with known L and R_{DCR}
SenseFET	Lossless, smaller area	Poor Accuracy due to V_{DS} mismatch
Modified SenseFET	Lossless, smaller area, relatively good accuracy	Accuracy depends upon transistor matching and op-amp BW
Current Transformer	Lossless	Not cost effective, bulky, can't be integrated on-chip

References

1. H. P. Forghani-zadeh and G. A. Rincón-Mora, “Current-sensing techniques for DC-DC converters,” in Proc. 2002 Midwest Symp. Circuits and Systems (MWSCAS), pp. 577–580.
2. E. Dallago, M. Passoni, and G. Sassone, “Lossless current-sensing in low-voltage high-current DC-DC modular supplies,” IEEE Trans. Ind. Electron., vol. 47, pp. 1249–1252, Dec. 2000.
3. H. P. Forghani-zadeh and G. A. Rincon-Mora, "An Accurate, Continuous, and Lossless Self-Learning CMOS Current-Sensing Scheme for Inductor-Based DC-DC Converters," in *IEEE Journal of Solid-State Circuits*, vol. 42, no. 3, pp. 665-679, March 2007.
4. Yang Zhang, R. Zane, A. Prodic, R. Erickson and D. Maksimovic, "Online calibration of MOSFET on-state resistance for precise current sensing," in *IEEE Power Electronics Letters*, vol. 2, no. 3, pp. 100-103, Sept. 2004.
5. S. Rao *et al.*, "A 1.2-A Buck-Boost LED Driver With On-Chip Error Averaged SenseFET-Based Current Sensing Technique," in *IEEE Journal of Solid-State Circuits*, vol. 46, no. 12, pp. 2772-2783, Dec. 2011.