

# EE155/255 Green Electronics

Transformers  
Isolated Converters

10/18/17

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Computer Systems Laboratory  
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# Course Logistics

- Monday is Solar Day
- HW 4 due next Monday 10/23
- Lab 3 must be checked off this week
- Lab 4 out this week

YAH

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Guest Lecture						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						

# Course to Date

- We need sustainable energy systems
- Voltage converters PSSA, buck and boost
- Real circuits: losses, dead-time, snubbers
- PV cells and systems
- Feedback control – PID
- Motors/generators current = torque, voltage = speed
- Today: isolated converters

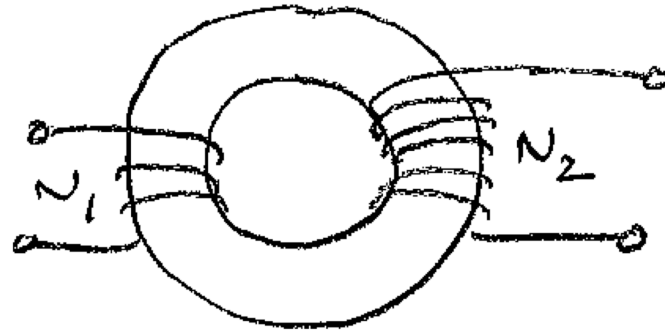
# Transformers

# Why Transformers?

- Galvanic isolation
  - Cannot tie DC GND to either side of AC line
  - Sometimes output must “float” (e.g., gate-drive supply)
- Large step-down or step-up
  - More efficient to use transformer when ratio is more than about 5:1
  - Reduced switching losses
  - Switches don't see both high current and high voltage
- Multiple outputs
  - Not restricted to just two windings

# Transformers

- Suppose I have two windings on a core
  - One with  $N_1$  turns, and one with  $N_2$  turns



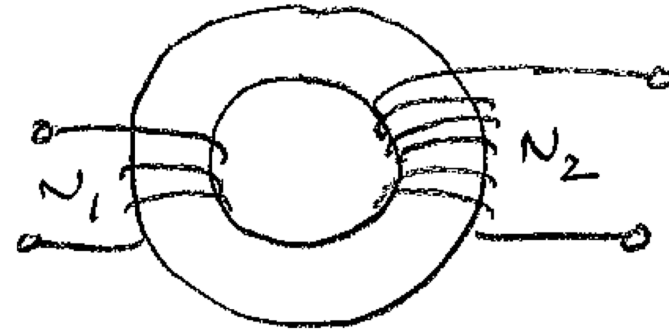
# Transformers

- Suppose I have two windings on a core
  - One with  $N_1$  turns, and one with  $N_2$  turns
  - We know

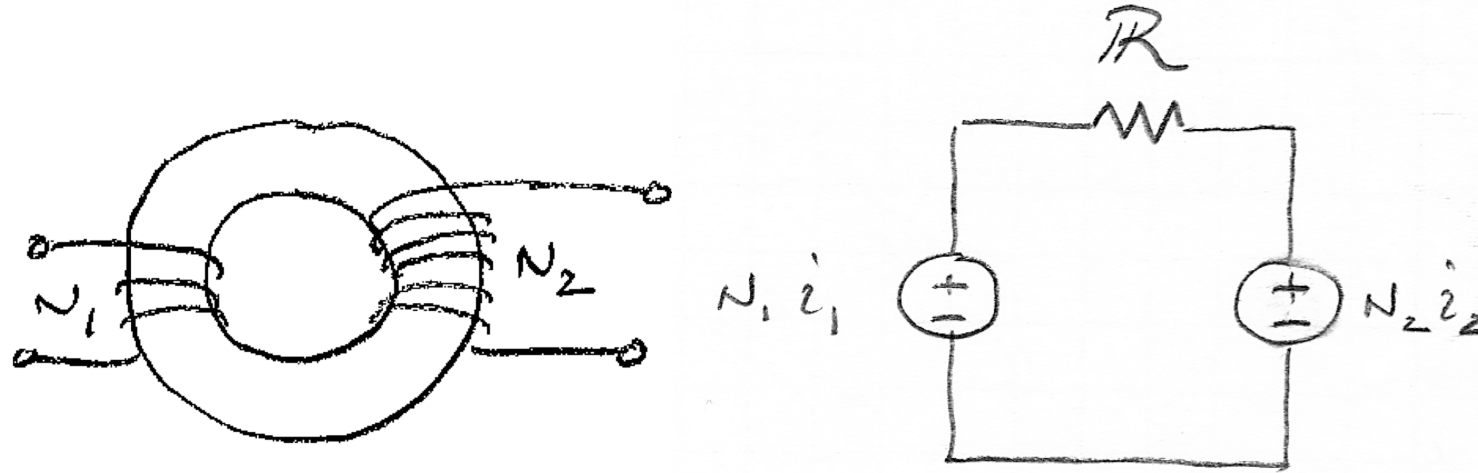
$$V_1 = N_1 \frac{d\phi}{dt}$$

$$V_2 = N_2 \frac{d\phi}{dt}$$

$$V_2 = \frac{N_2}{N_1} V_1$$



# Equivalent Magnetic Circuit

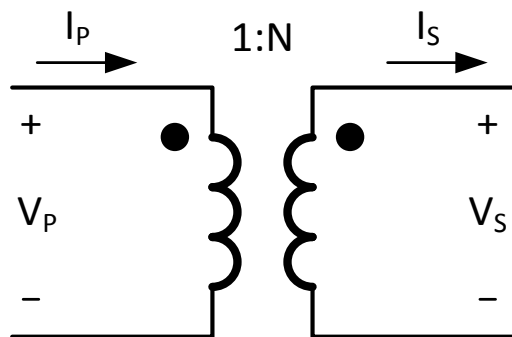


If reluctance were zero we would have

$$N_1 i_1 = N_2 i_2$$

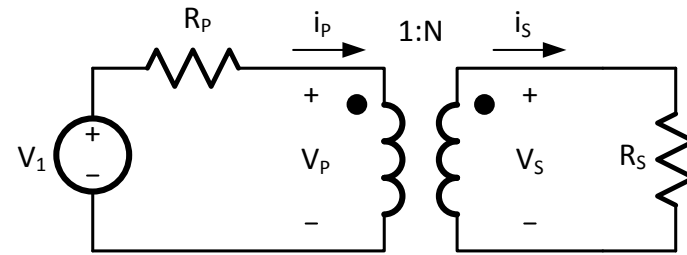
$$i_2 = \left( \frac{N_1}{N_2} \right) i_1$$

# Ideal Transformer

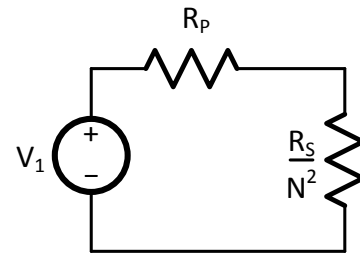


$$V_S = \frac{N_S}{N_P} V_P$$
$$I_S = \frac{N_P}{N_S} V_P$$

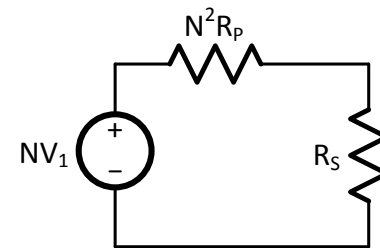
# Example Circuit



(a) Example circuit

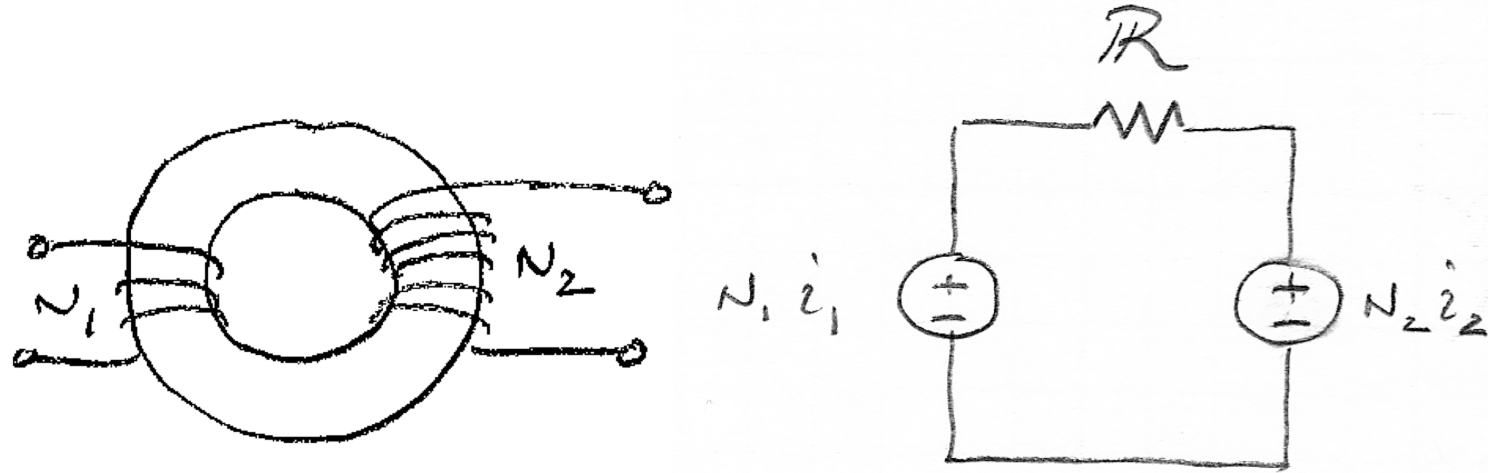


(b) Referenced to primary



(c) Referenced to secondary

# Equivalent Magnetic Circuit

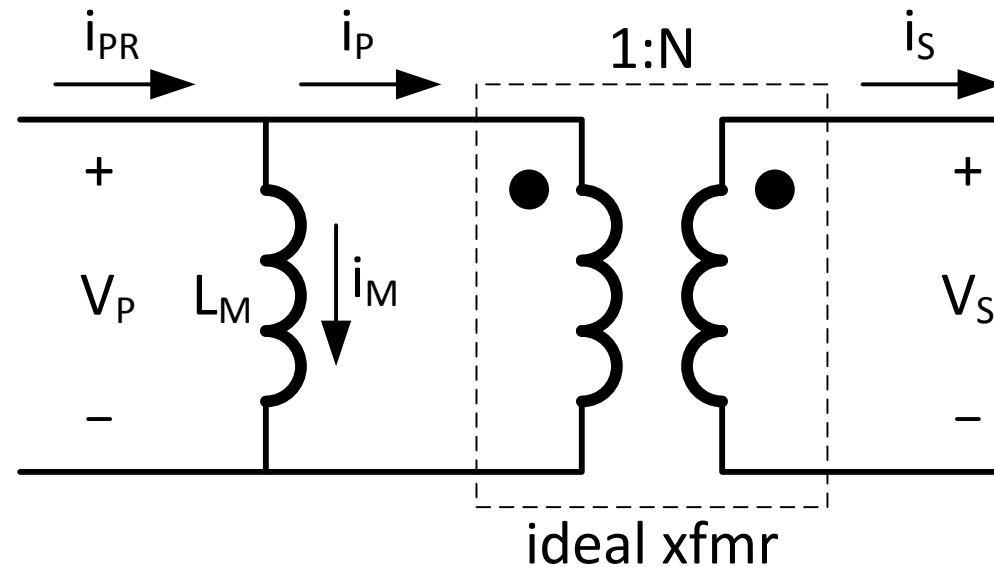


With reluctance we have

$$N_1 i_1 = N_2 i_2 + \mathcal{R} \phi$$

$$i_2 = \left( \frac{N_1}{N_2} \right) i_1 + \frac{\mathcal{R}}{N_1^2} \int V dt$$

# Model as Ideal Transformer in Parallel with Magnetizing Inductance (Superposition)



$$L_m = \frac{N_1^2}{\mathcal{R}}$$

# Transformer Saturation

- Transformer can pass high current from primary to secondary without saturating
- Saturation is due to magnetizing inductance
- Magnetizing flux is proportional to VT (volt-seconds)
- Choose N (number of turns) for required VT at specified max B
- VT must be *balanced* (sum to zero each cycle).

$$V = N \frac{d\phi}{dt}$$

$$VT = N\phi$$

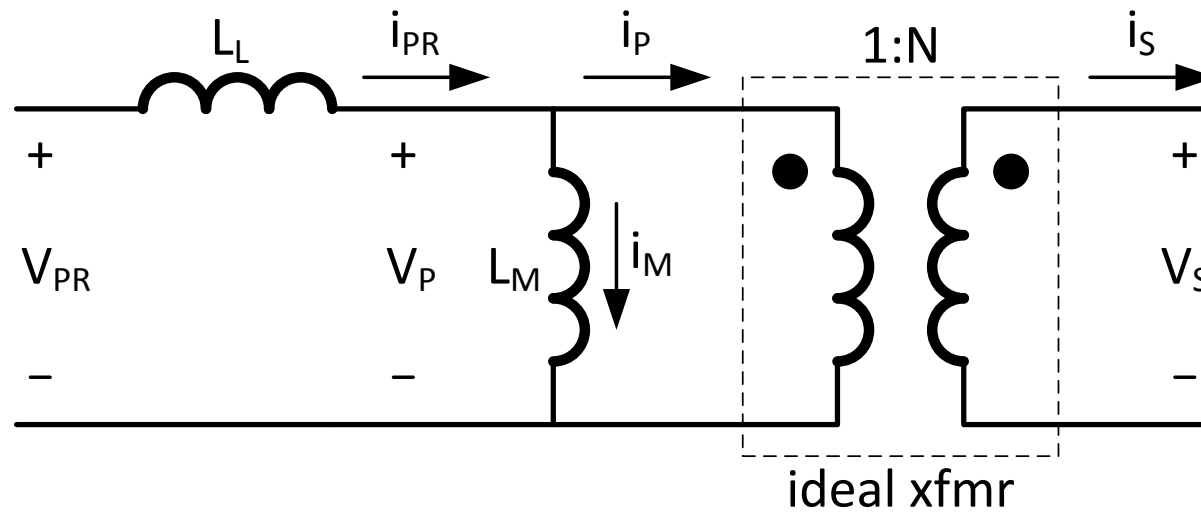
$$VT = NBA$$

$$N = \frac{VT}{BA}$$

# Leakage Inductance

- Flux that is not linked by both windings results in *leakage inductance*
  - Typically 1-5% of total inductance
  - Larger for gapped cores (due to fringing)
  - Can be reduced by ‘interleaving’ windings
- Can be reflected to primary or secondary
  - But one inductance on each side of magnetizing inductance
  - We will approximate this as all being on the primary side

# Model with Leakage Inductance



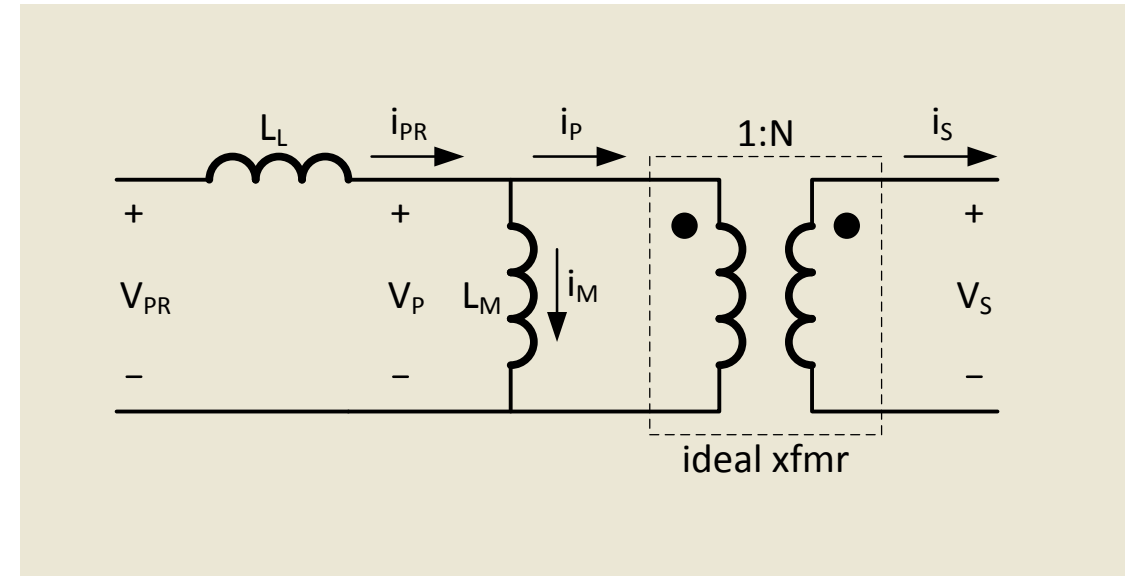
# Magnetizing and Leakage Inductance

- Magnetizing inductance

- Sets minimum operating frequency
- Too long an input pulse
  - Saturates transformer
  - Gives large  $\Delta B$  – large core loss

- Leakage inductance

- Sets maximum operating frequency (and maximum duty factor)
- Have to zero (or reverse) current in leakage inductance each cycle
  - Results in “commutation period”
- Typically 2-10% of  $L_M$  depending on winding geometry



# SPICE Model of a Transformer

```
* Transformer Model
* Does not include core loss
* Make Ls very large (1000x Lm)
* N:1 primary:secondary
* Lx is leakage Lm is magnetizing inductance
.subckt xfrmr PP PN SP SN
RP PP X {Rs*N*N}
LM X Y {Lm}
LP X Y {N*N*Ls}
LX Y PN {Lx}
LS SP Z {Ls}
RS Z SN {Rs}
K LP LS 1
.ends
```

# Transformer Converters

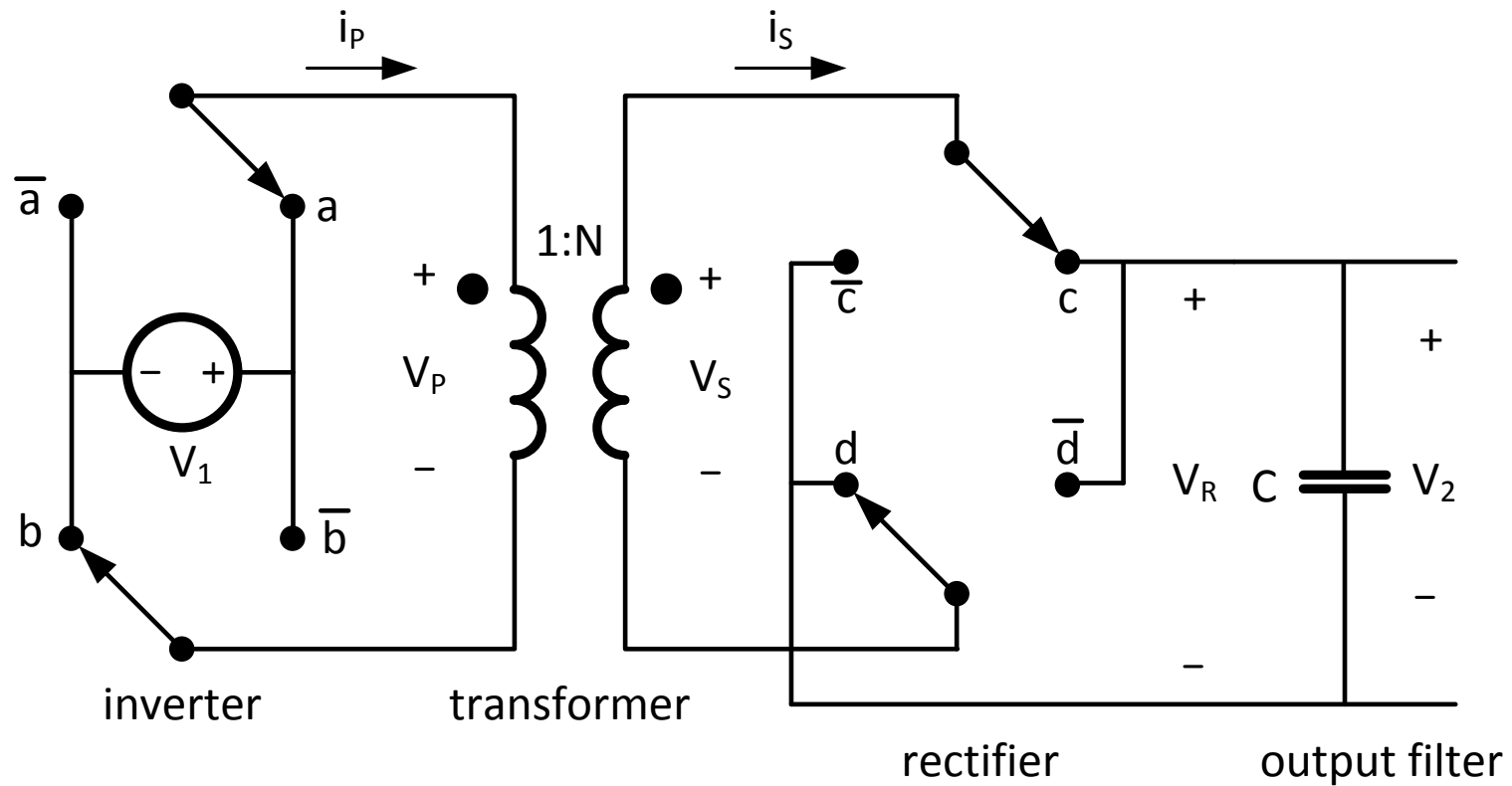
# Transformer Converters

- Use a transformer to provide step-up/step-down
  - Still also require an inductor for energy storage
- Bridge converters (full-bridge and half-bridge)
  - Voltage-fed – like a buck
  - Current-fed – like a boost
- Forward converter
  - Like a buck
  - Inductor in secondary circuit
- Flyback converter
  - Like a buck/boost
  - Uses magnetizing inductance for energy storage
  - Primary and secondary conduct during different phases

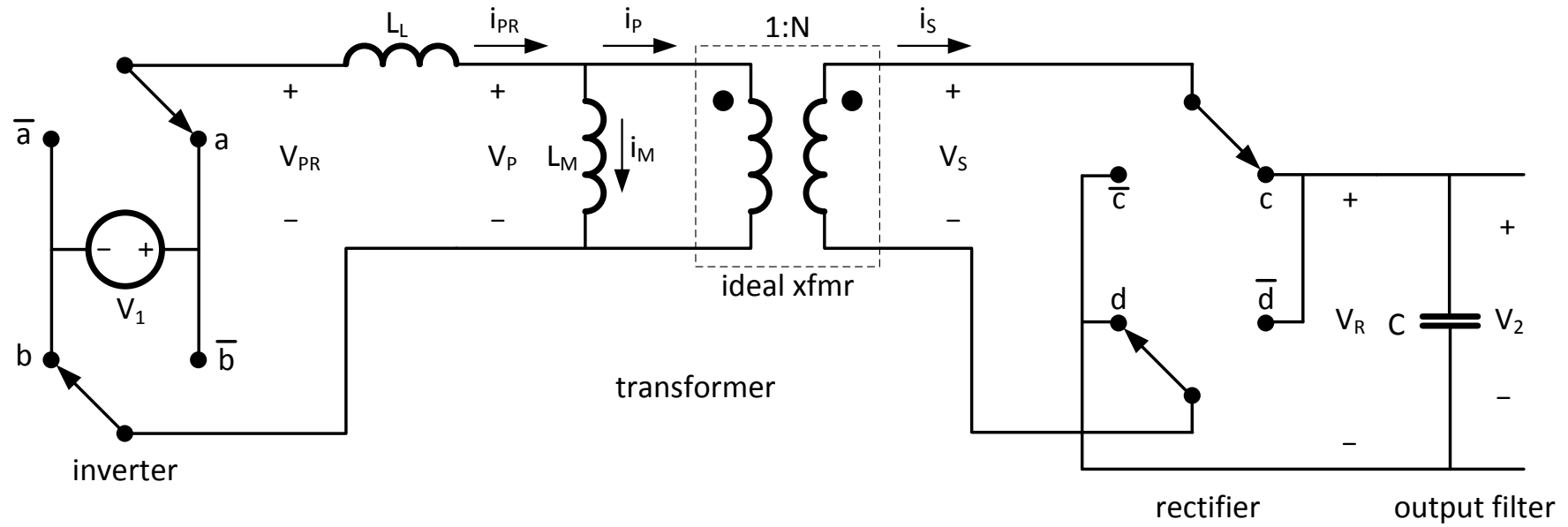
# Analyzing Transformer Converters

- Divide cycle into *phases*
- In each phase determine which winding sets the transformer voltage
- Voltage across each inductor (including  $L_m$  and  $L_l$ ) determines current slope

# Bad Converter

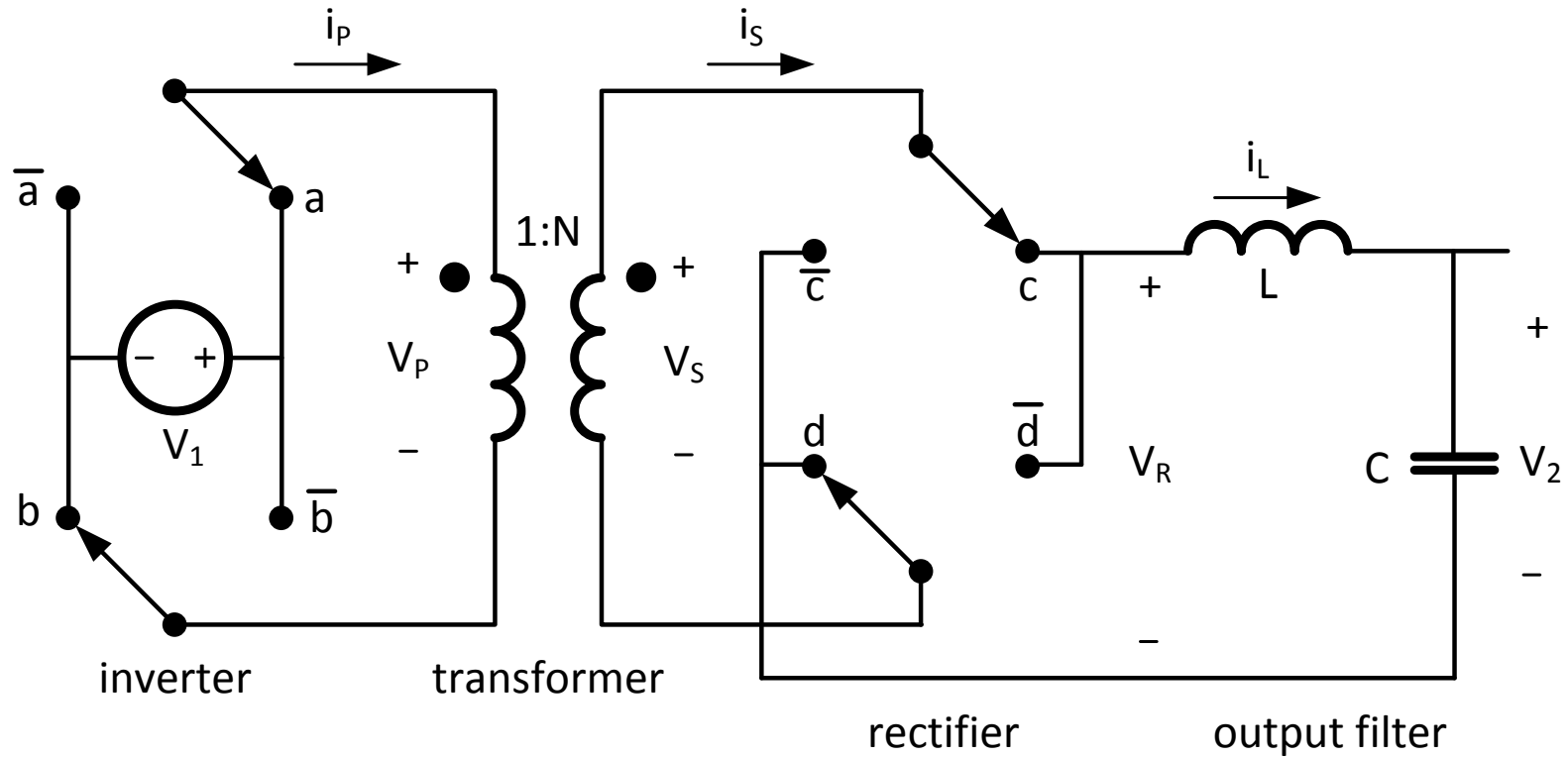


# Bad Converter

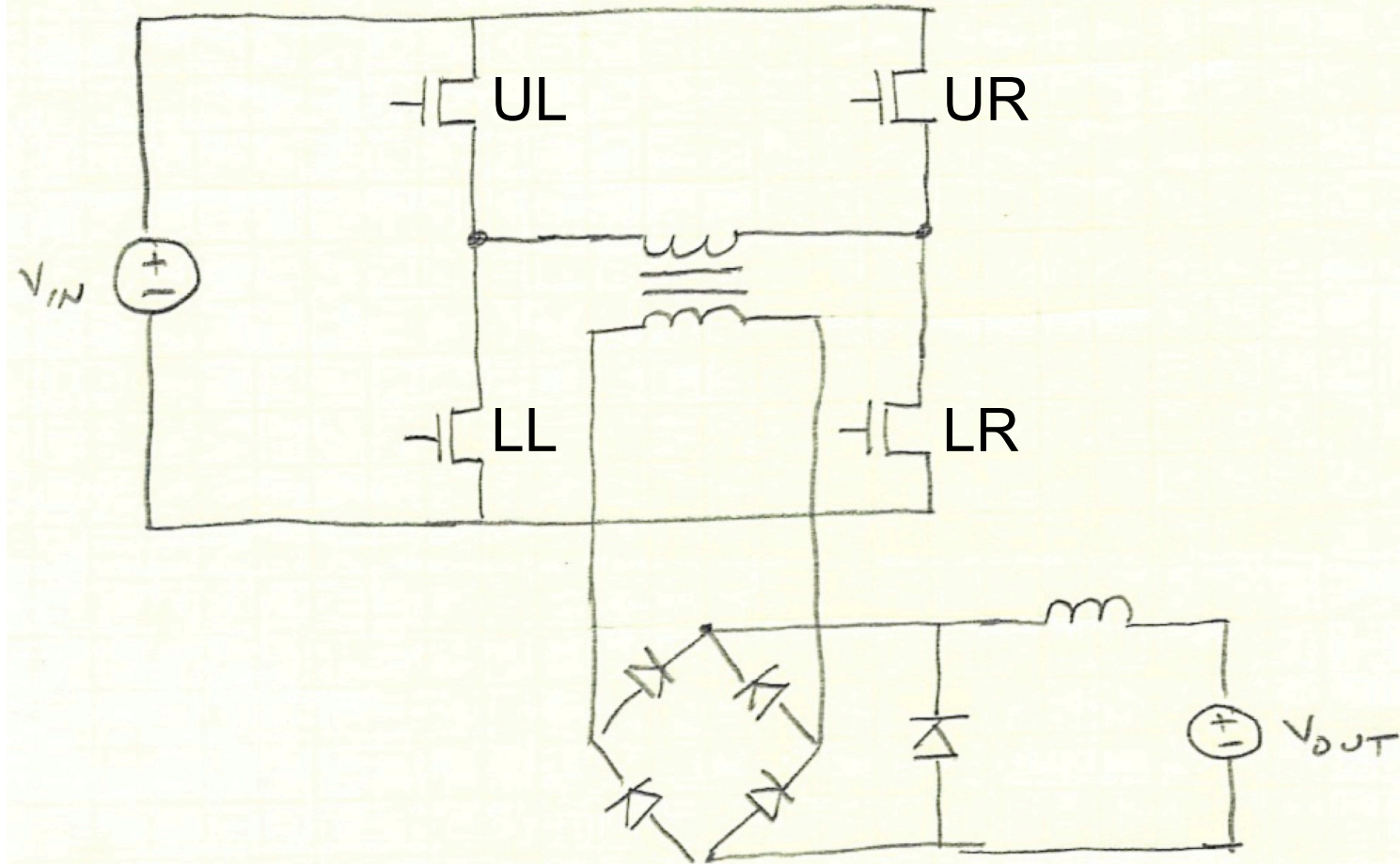


# Full-Bridge Converter

# Full-Bridge Converter



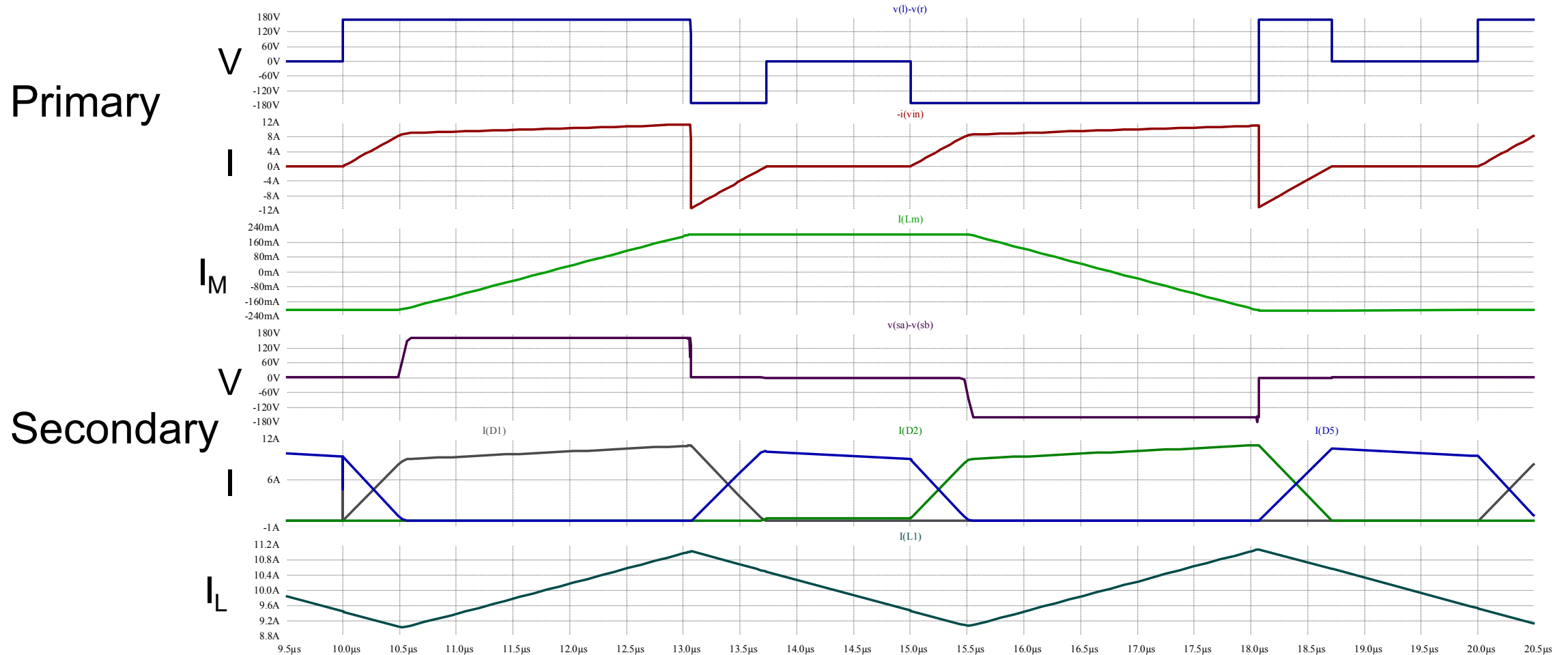
# Full-Bridge Converter



# Full Bridge Operation

1. UL and LR on
  - $V_{in}$  across primary
  - $NV_{in}-V_{out}$  across inductor
2. All off (or LL and LR on)
  - Leakage energy returned to supply (soft switching)
  - Secondary shorted
  - Magnetizing current circulates in secondary
3. UR and LL on
  - $-V_{in}$  across primary
  - $NV_{in}-V_{out}$  across inductor
  - Magnetizing current balanced out
4. All off (or LL and LR on)

# SPICE Waveforms for Bridge Converter



Interval 1:

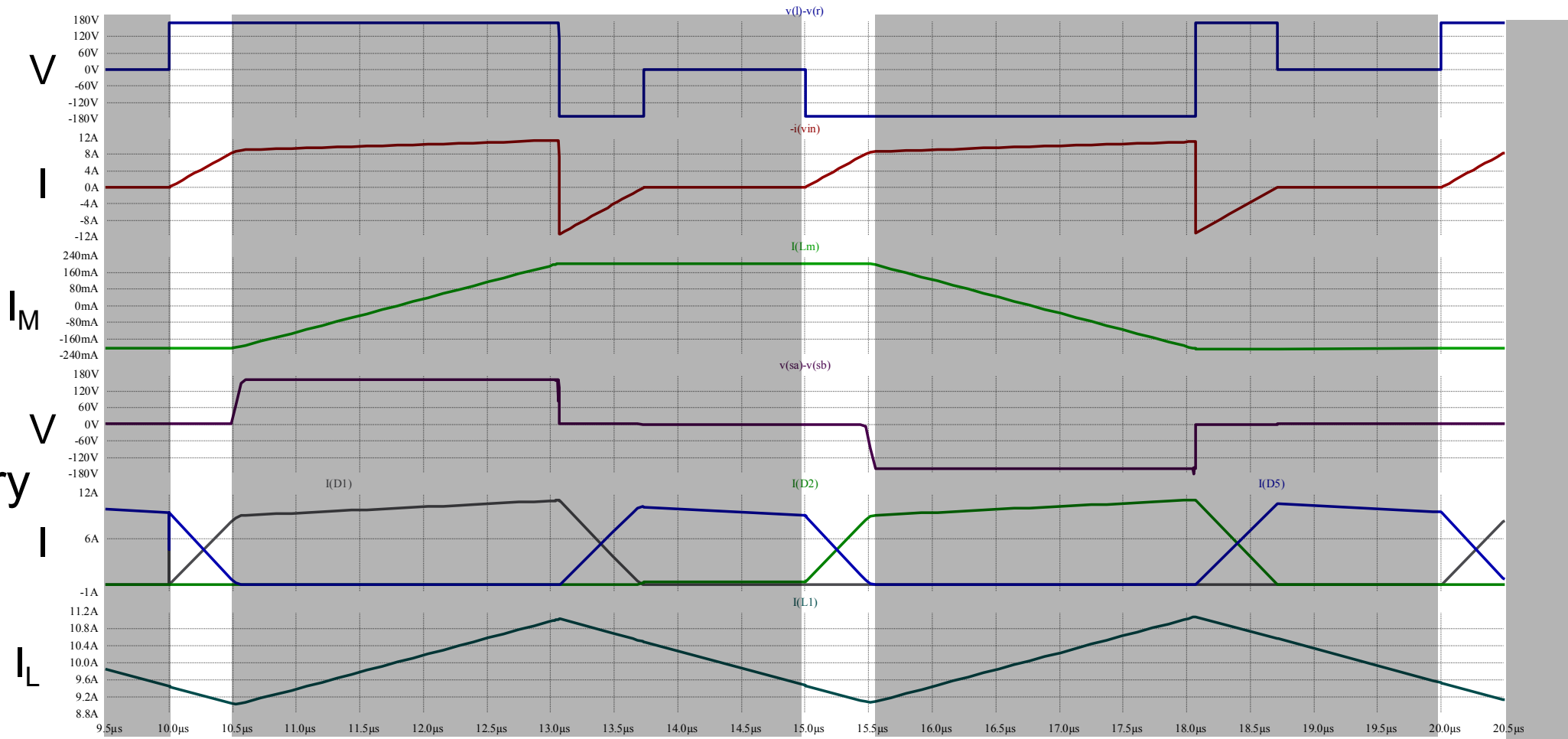
# Commutation – On

Apply voltage to primary

Diode clamps secondary

Current ramps up in leakage inductance

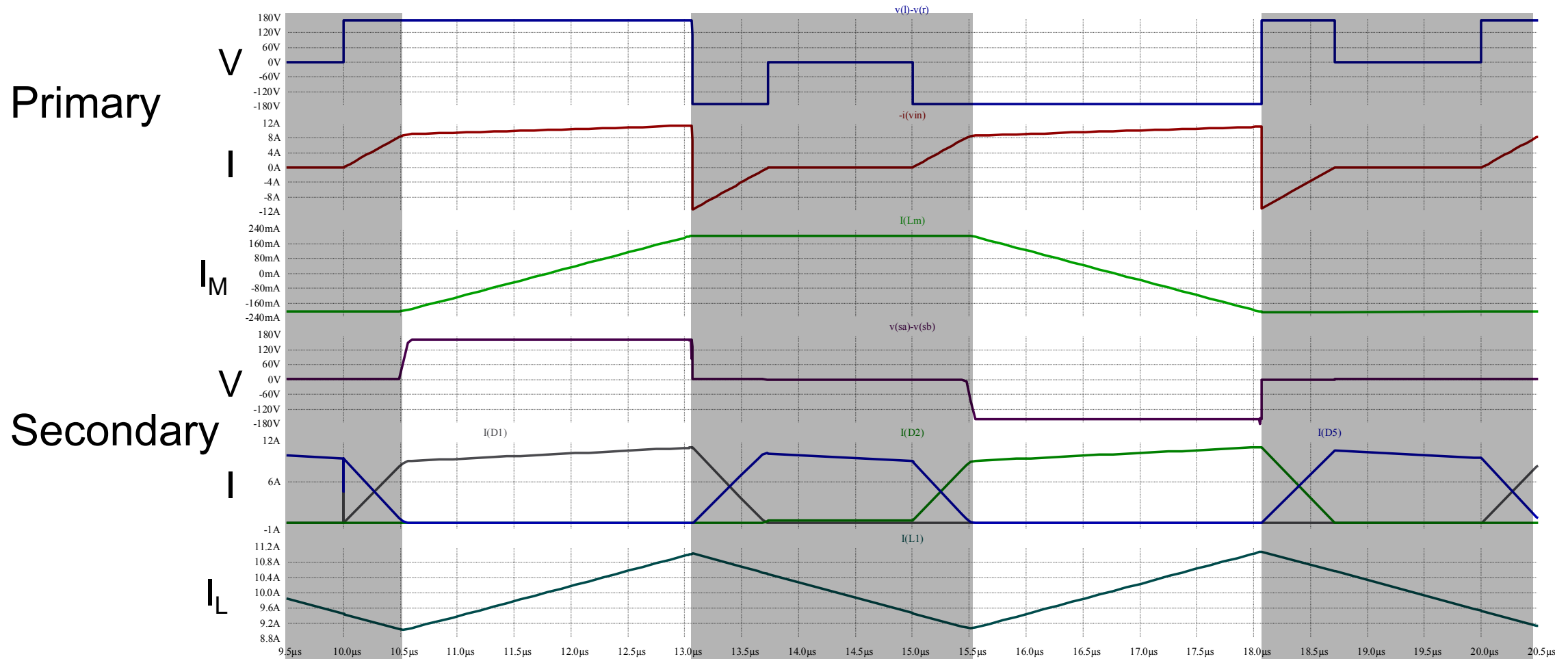
Primary



# Interval 2:

## Drive

- Leakage current matches output current
- Secondary drives output inductor
- Current ramps in output inductance



Interval 3:

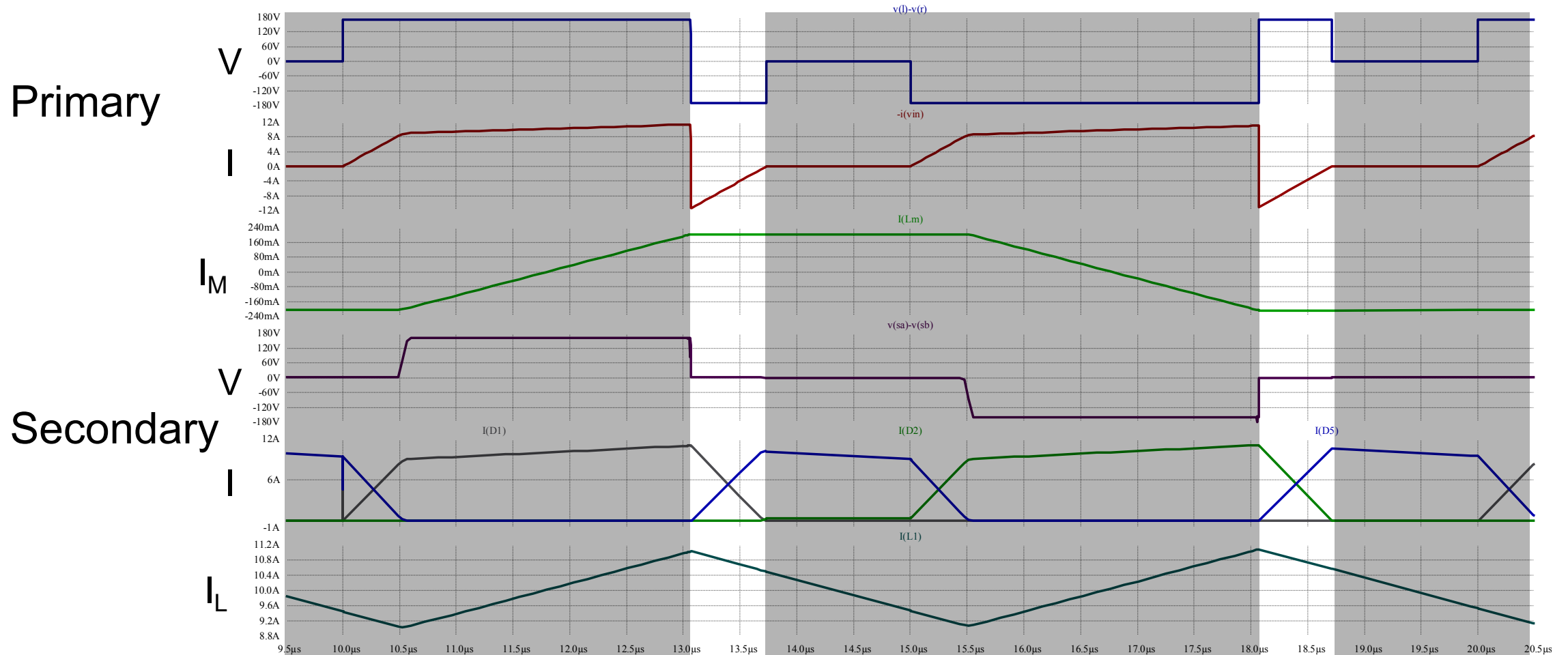
### Commutation – Off

Primary turns off

Diode clamps secondary

Leakage energy returns to supply

Current ramps down in leakage inductance



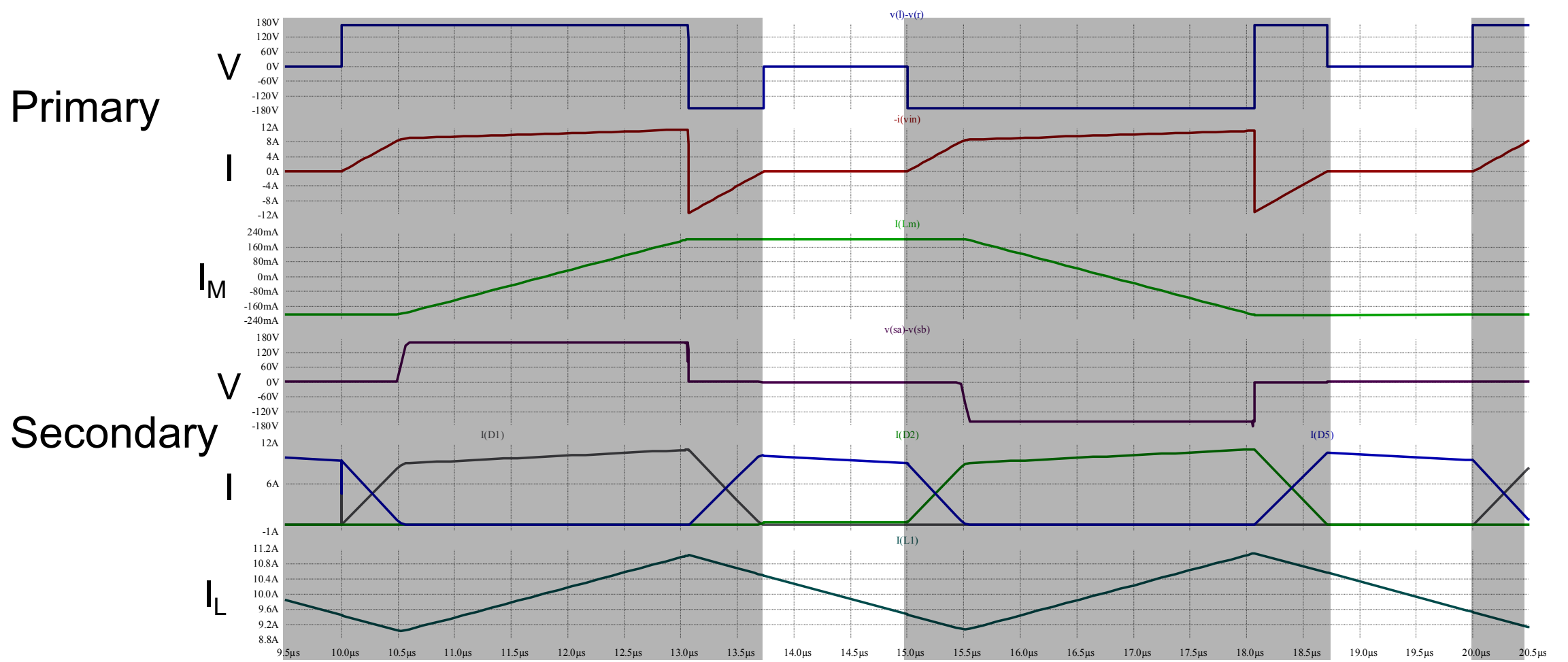
Interval 4:

### Idle

Leakage current reaches zero

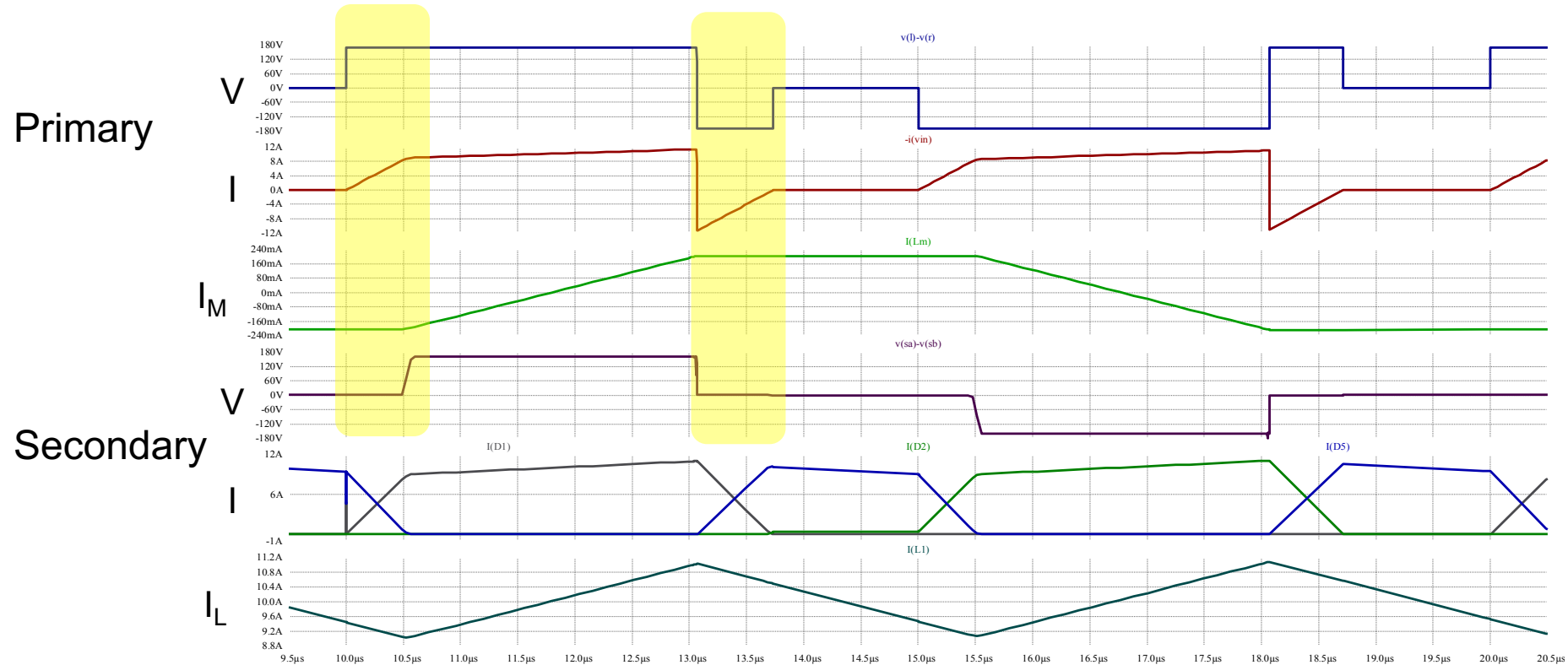
Secondary remains clamped

Current ramps down in output inductance

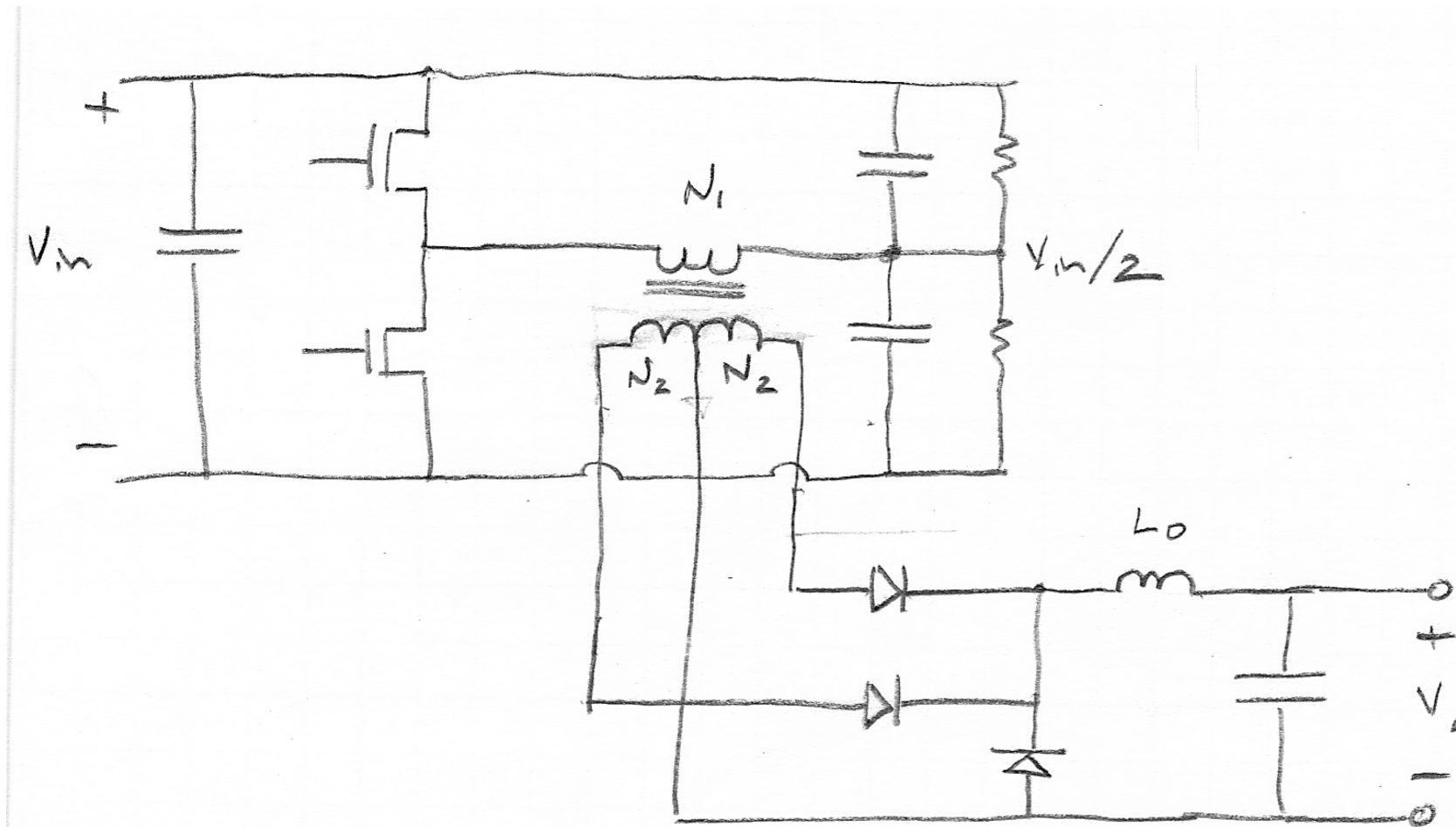


# Commutation

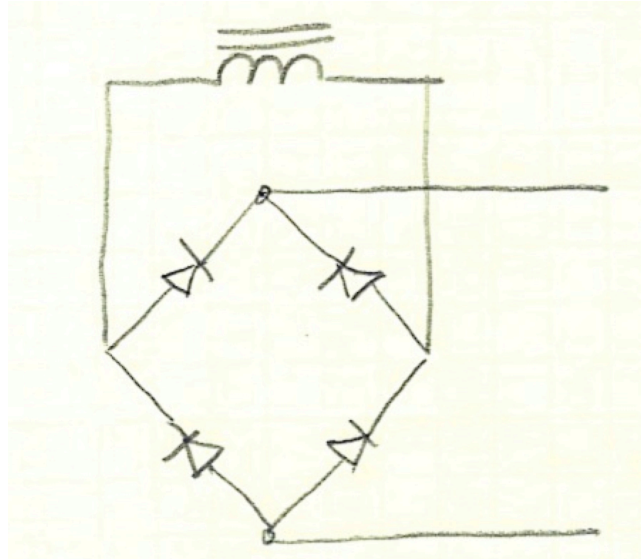
- Duty factor of secondary reduced by commutation-on delay
- Duty factor of primary limited by commutation-off delay
- What is the total commutation time? What is the maximum secondary DF?



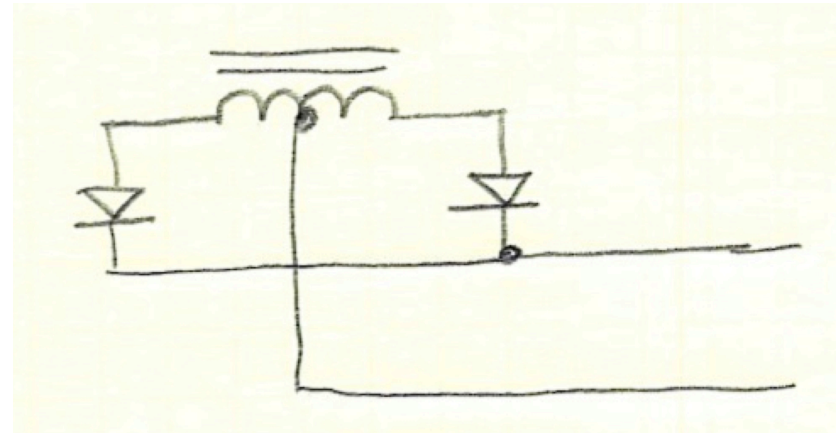
# Half-Bridge Converter With Center-Tapped Secondary



# Secondary Circuits



Full bridge  
Less copper  
Two diode drops  
Lower voltage diodes

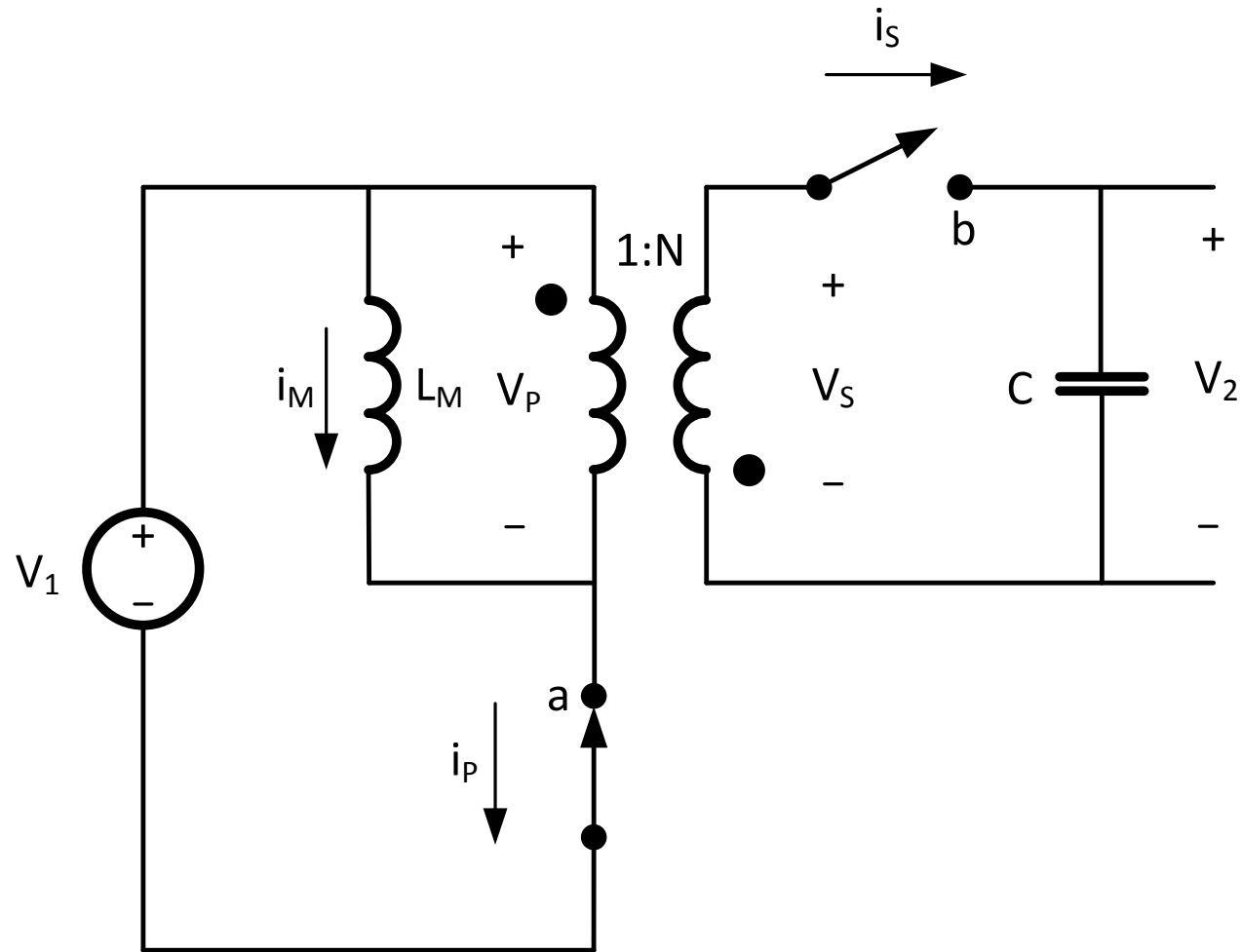


Center-tapped secondary  
Twice the copper  
One diode drop  
Higher voltage diodes

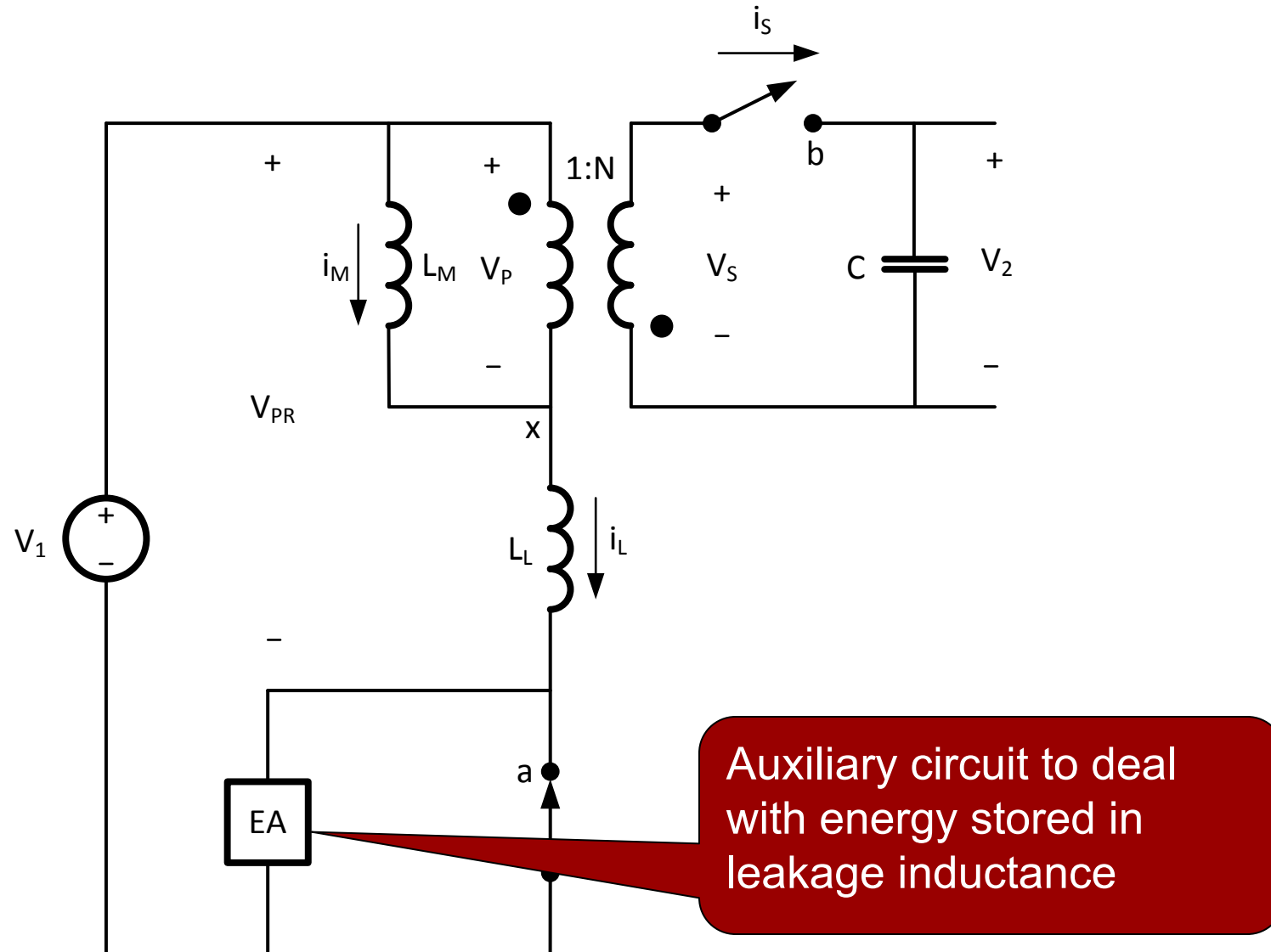
Either can use synchronous rectification

# Flyback Converter

# Flyback Converter

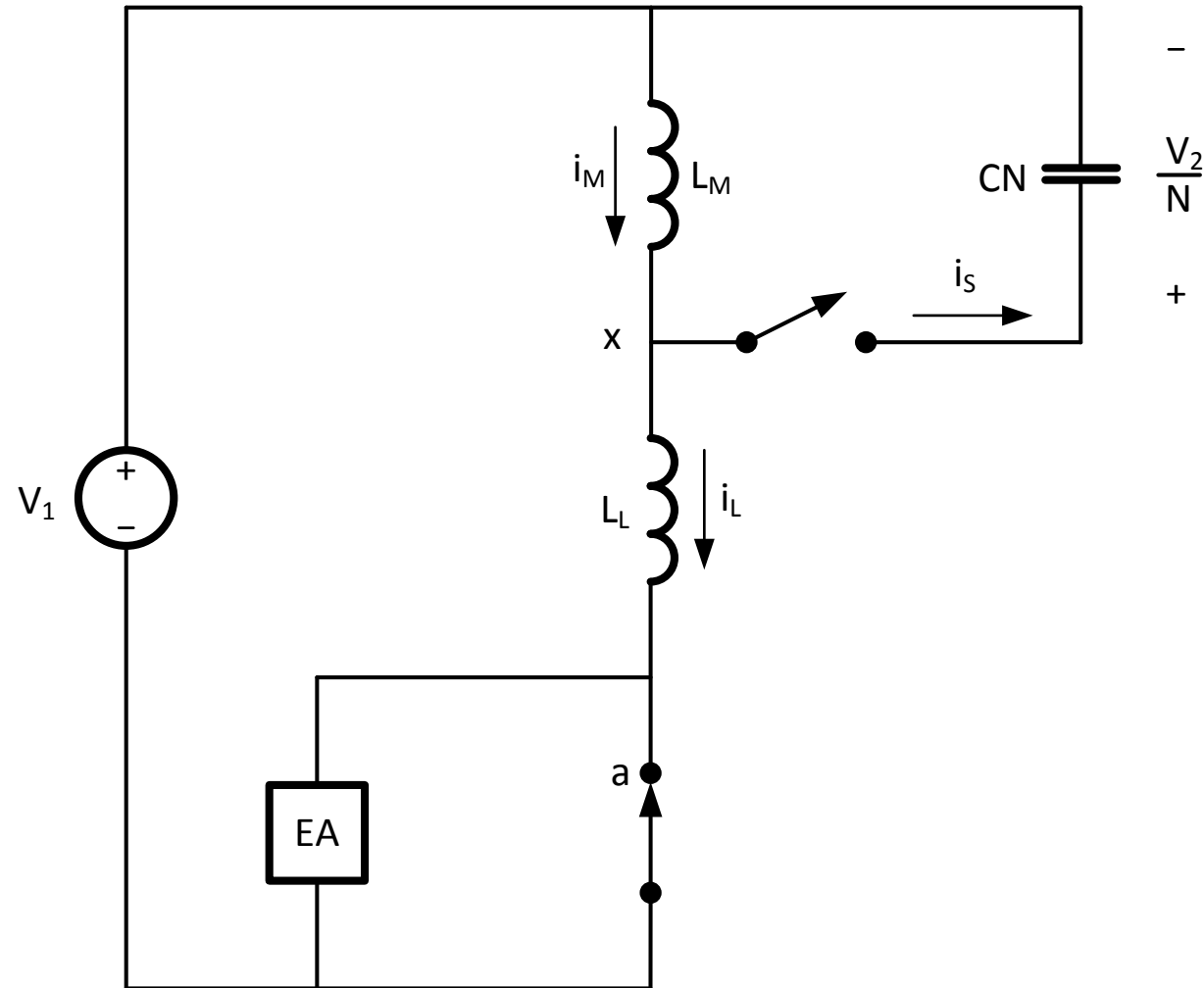


# Flyback with Leakage Inductance



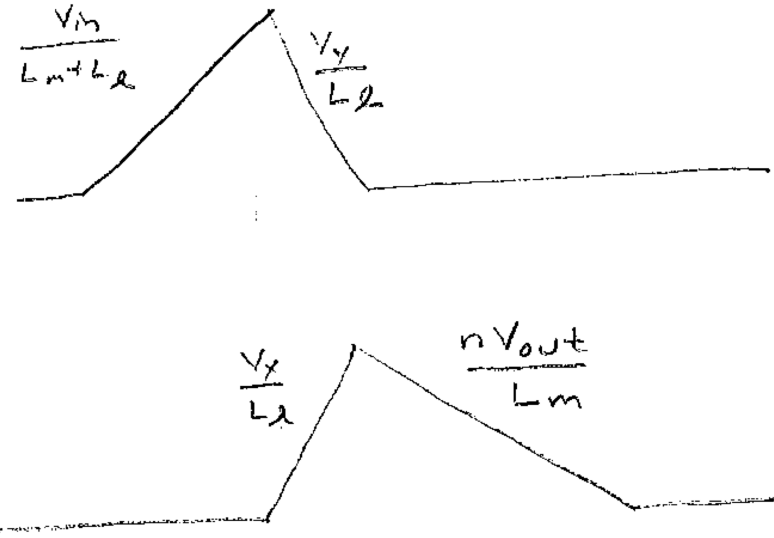
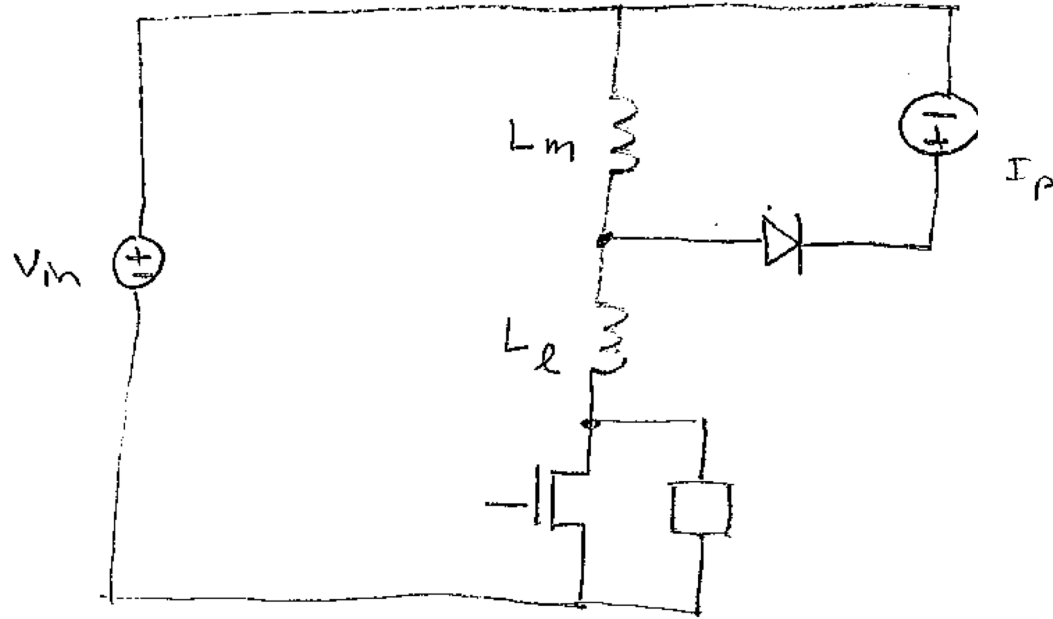
# Flyback Converter

## Adding $L_M$ and $L_L$ and Eliminating Transformer

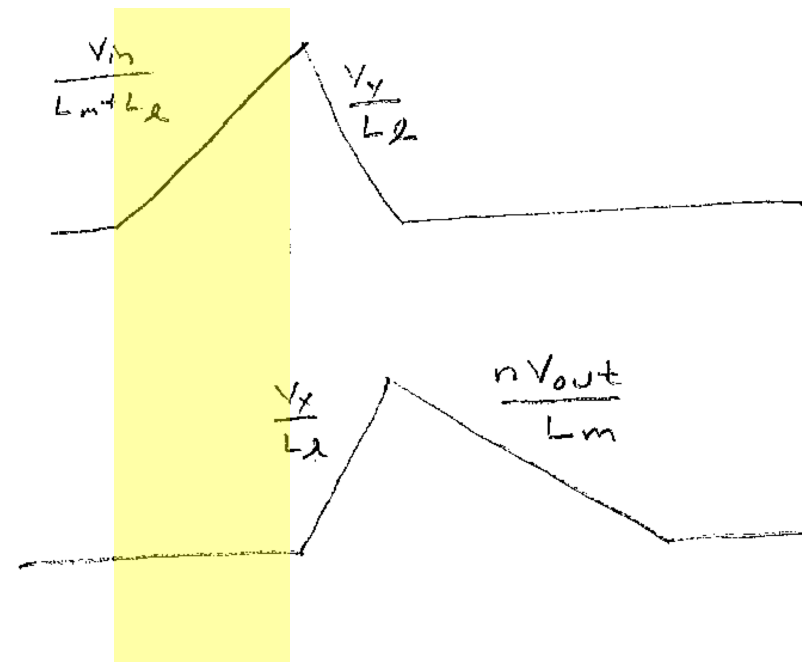
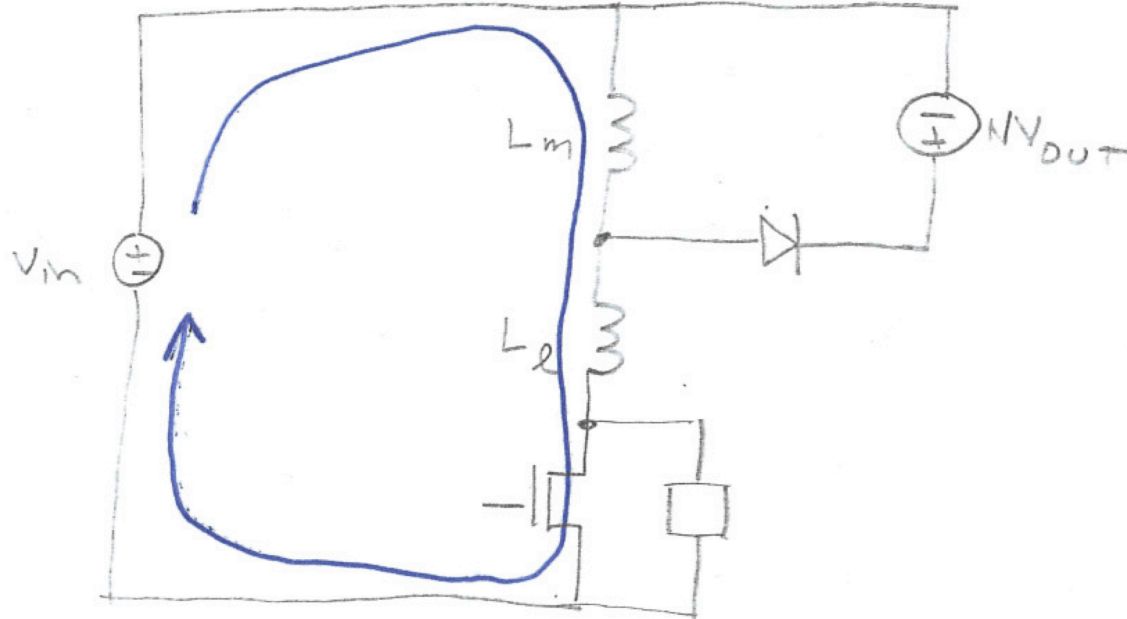


# Flyback Operates in 4 Phases

## DCM Shown Here



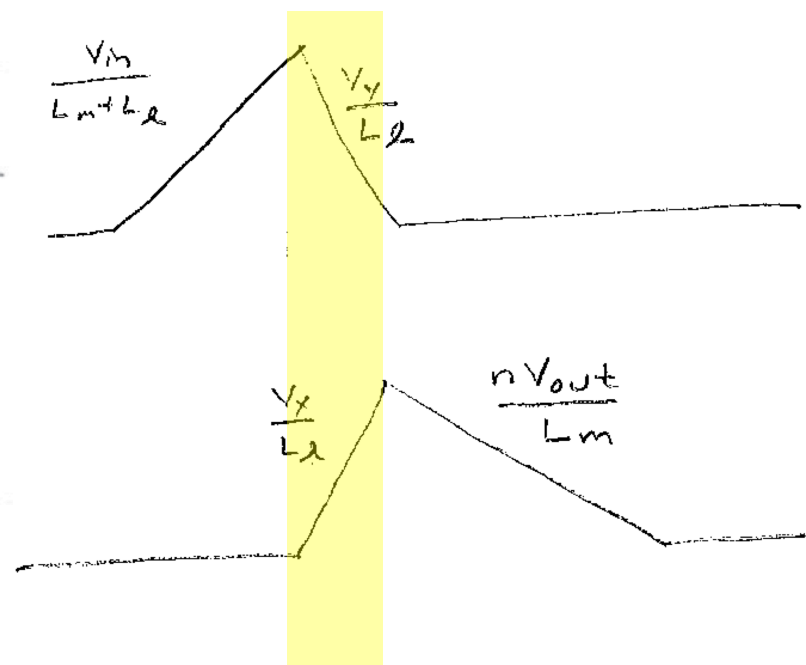
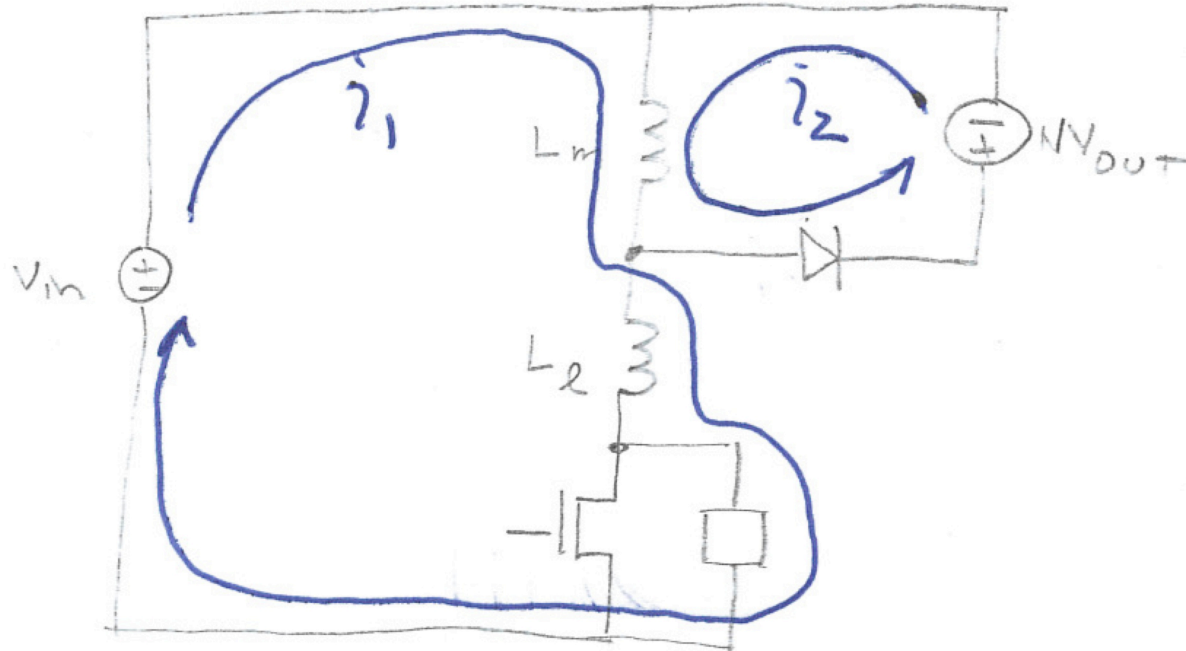
# Flyback Phase 1: Primary Conduction



Phase 1: Current ramps in  $L_m + L_l$

$$\Delta I = V_{in} \Delta t / (L_m + L_l)$$

# Flyback Phase 2: Commutation



## Phase 2: Commutation

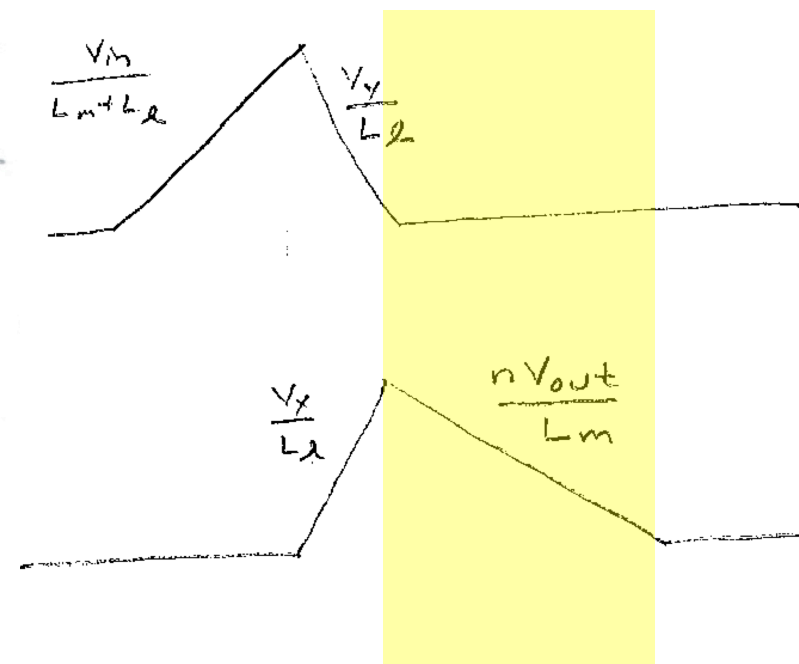
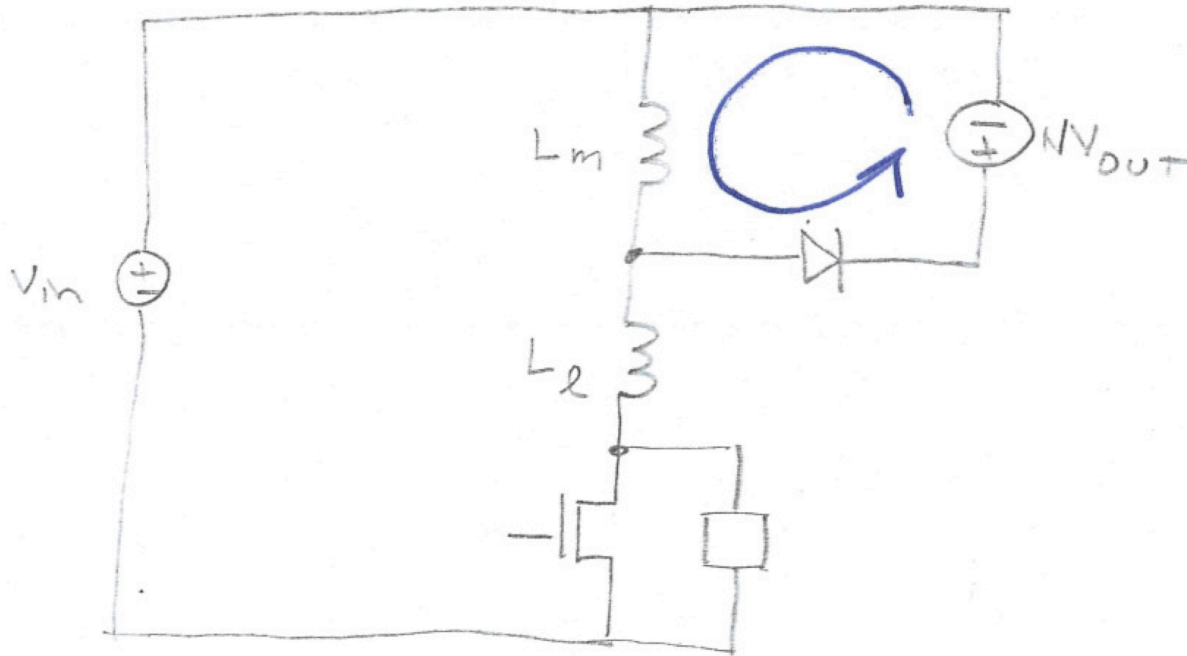
Diode clamps junction to  $V_{in} + nV_{out}$

Aux circuit applies voltage across  $L_1$

Current ramps down in  $L_1$   $\Delta I = -V_y \Delta t / L_1$

Secondary current ramps up by same amount

# Flyback Phase 3: Secondary Conducts



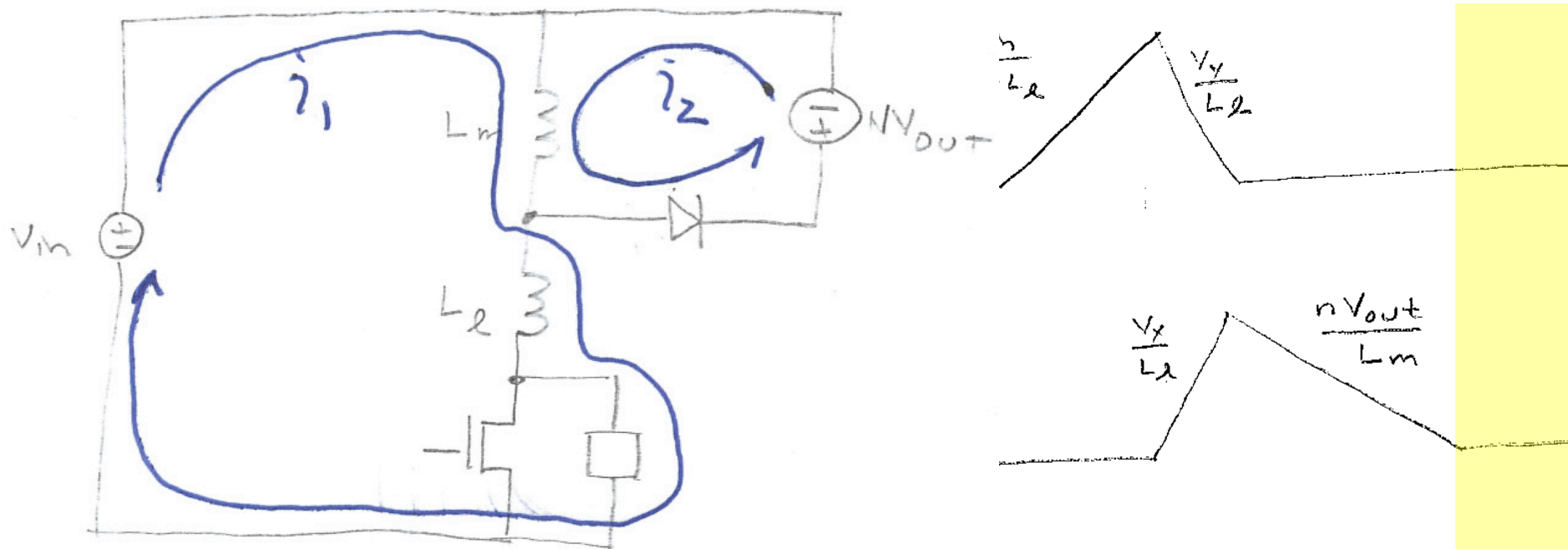
## Phase 3: Secondary Conducts

Diode clamps junction to  $V_{in} + nV_{out}$

Current ramps down in  $L_m$   $\Delta I = -nV_y \Delta t / L_l$

$L_m$  rings with  $C_d$

# Flyback Phase 4: Off (DCM), Commutation (CCM)



## Phase 4: Off/Commutation

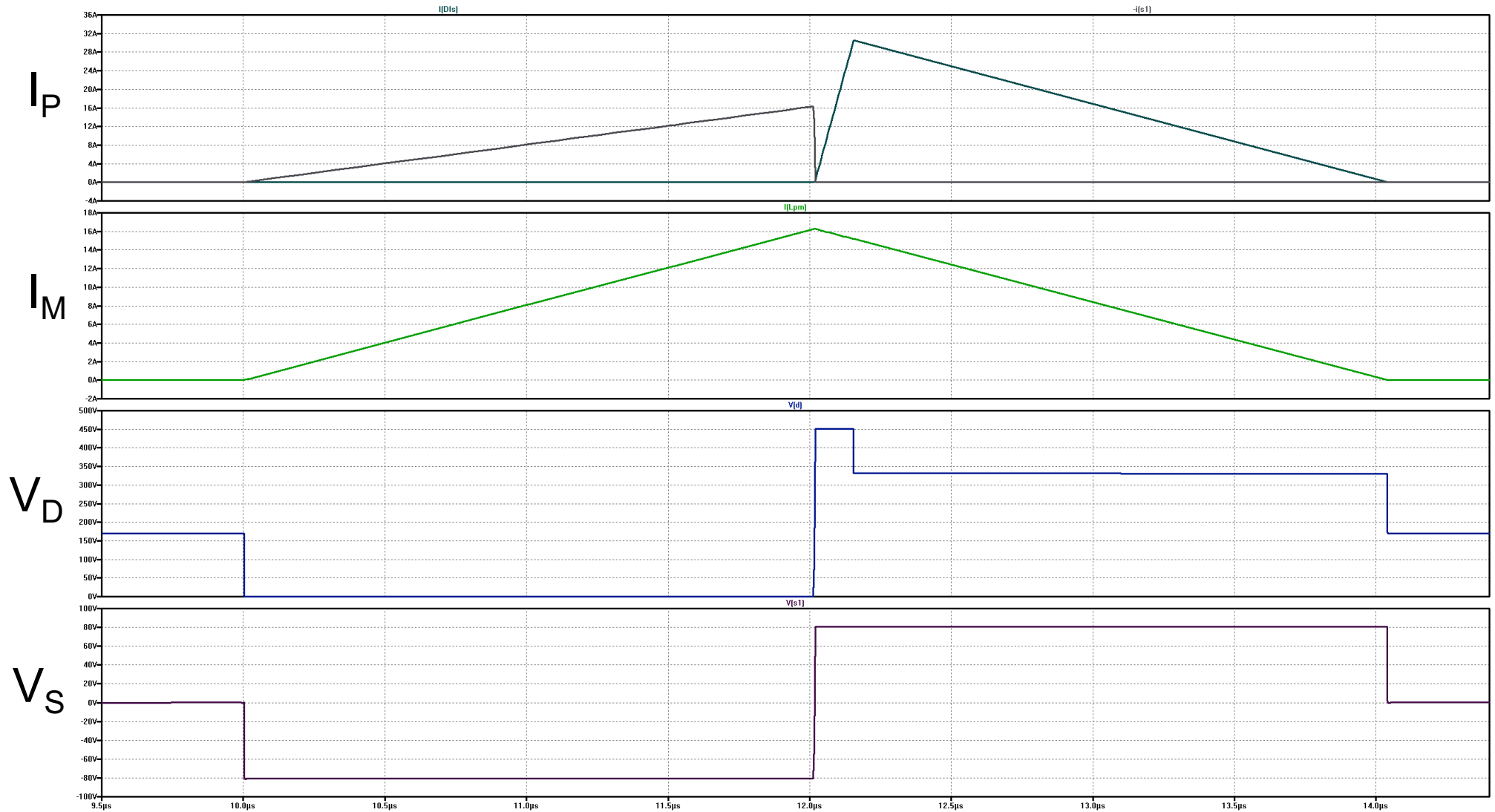
Diode clamps junction to  $V_{in} + nV_{out}$

$V_{in} + nV_{out}$  across  $L_1$

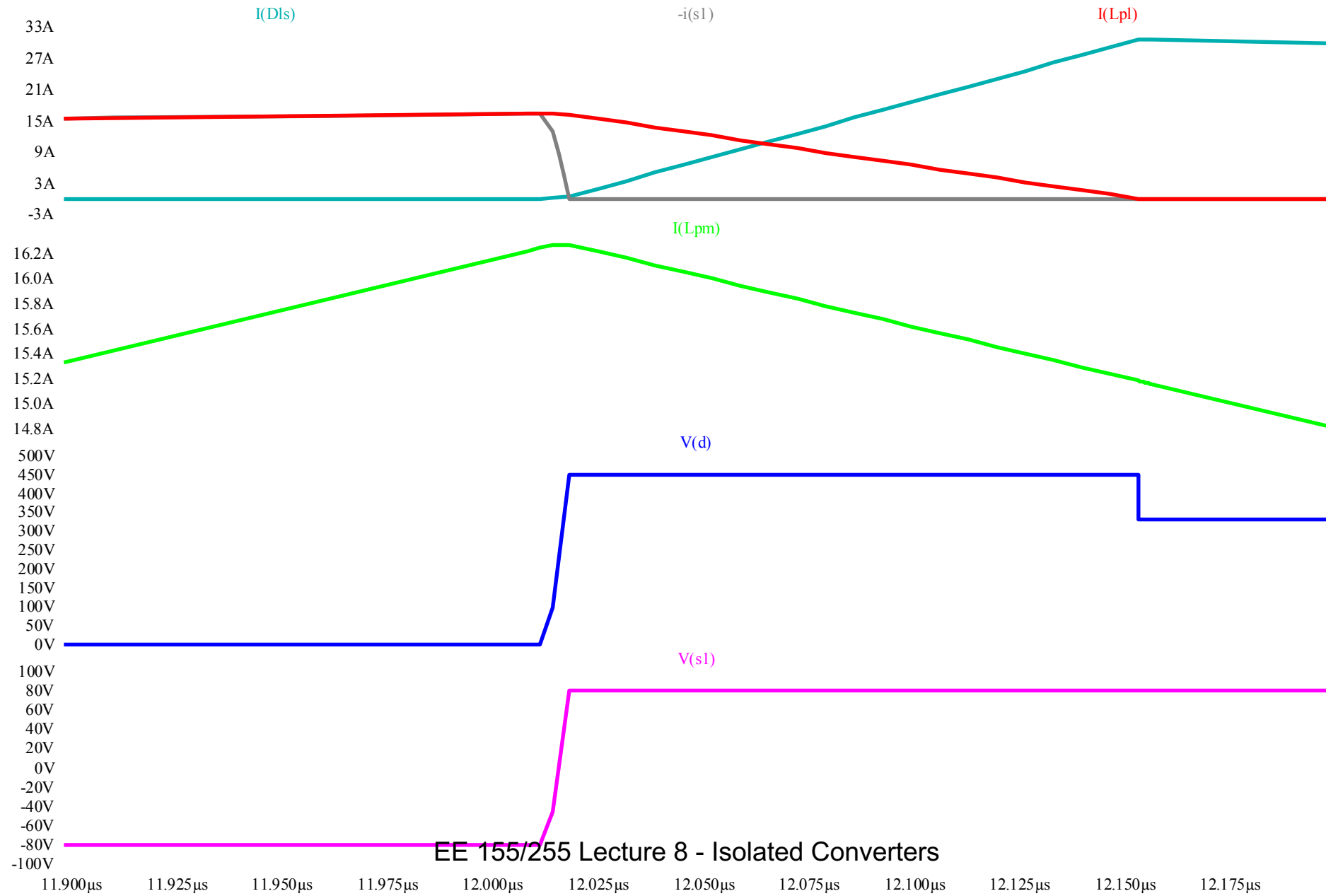
Current ramps up in  $L_1$   $\Delta I = (V_{in} + nV_{out})\Delta t/L_1$

Secondary current ramps down by same amount

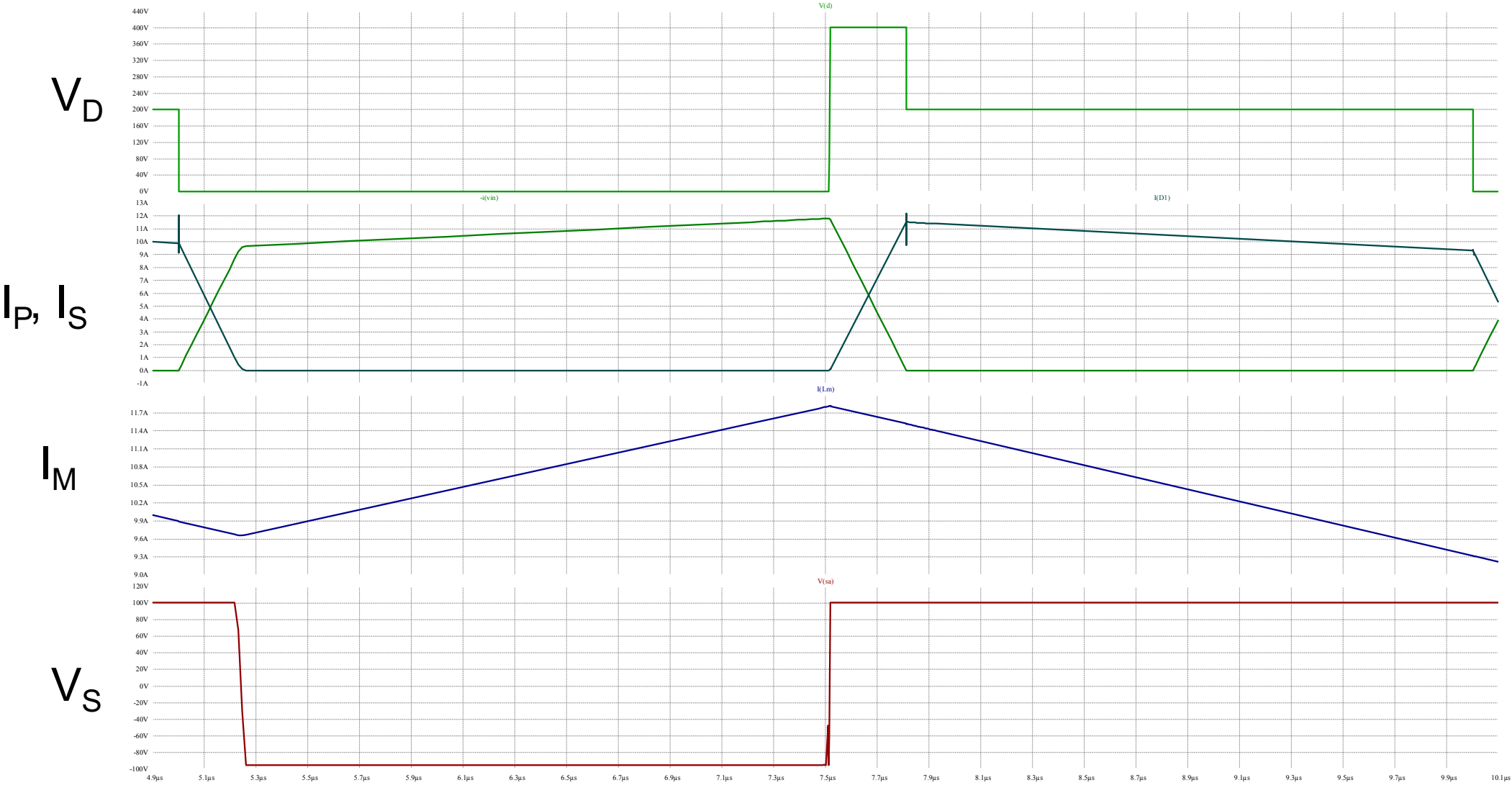
# Flyback SPICE Waveforms



# Zoom of Commutation Phase



# SPICE of Flyback in CCM



# SPICE Deck

```
* test of lossless single-switch flyback converter
```

```
.param Vin=170 Vout=80
```

```
.param Cr=10n
```

```
.param Tcy=10u Tw=2u Ncy=3
```

```
.model D1 D(Ron=0.01 Roff=1000k Vfwd=0.4)
```

```
VIN IN 0 {Vin}
```

```
VOUT OUT 0 {Vout}
```

```
* Transformer
```

```
LPL IN P1 1u
```

```
RP P1 P2 0.01
```

```
LPM P2 D 20u
```

```
LP P2 D 4m
```

```
LS 0 S1 1m
```

```
K LP LS 1
```

```
* switch
```

```
S1 D 0 G 0 SW1
```

```
.model SW1 SW(Ron=.01 Roff=1000k Vt=5)
```

```
DS1 0 D D1
```

```
* Output diode
```

```
DLS S1 OUT D1
```

```
* recovery
```

```
DR1 D CRP D1
```

```
VR CRP 0 450
```

```
* pulse
```

```
VG G 0 PULSE(0 15 0 10n 10n {Tw} {Tcy} {Ncy})
```

```
.ic v(CRN) 0
```

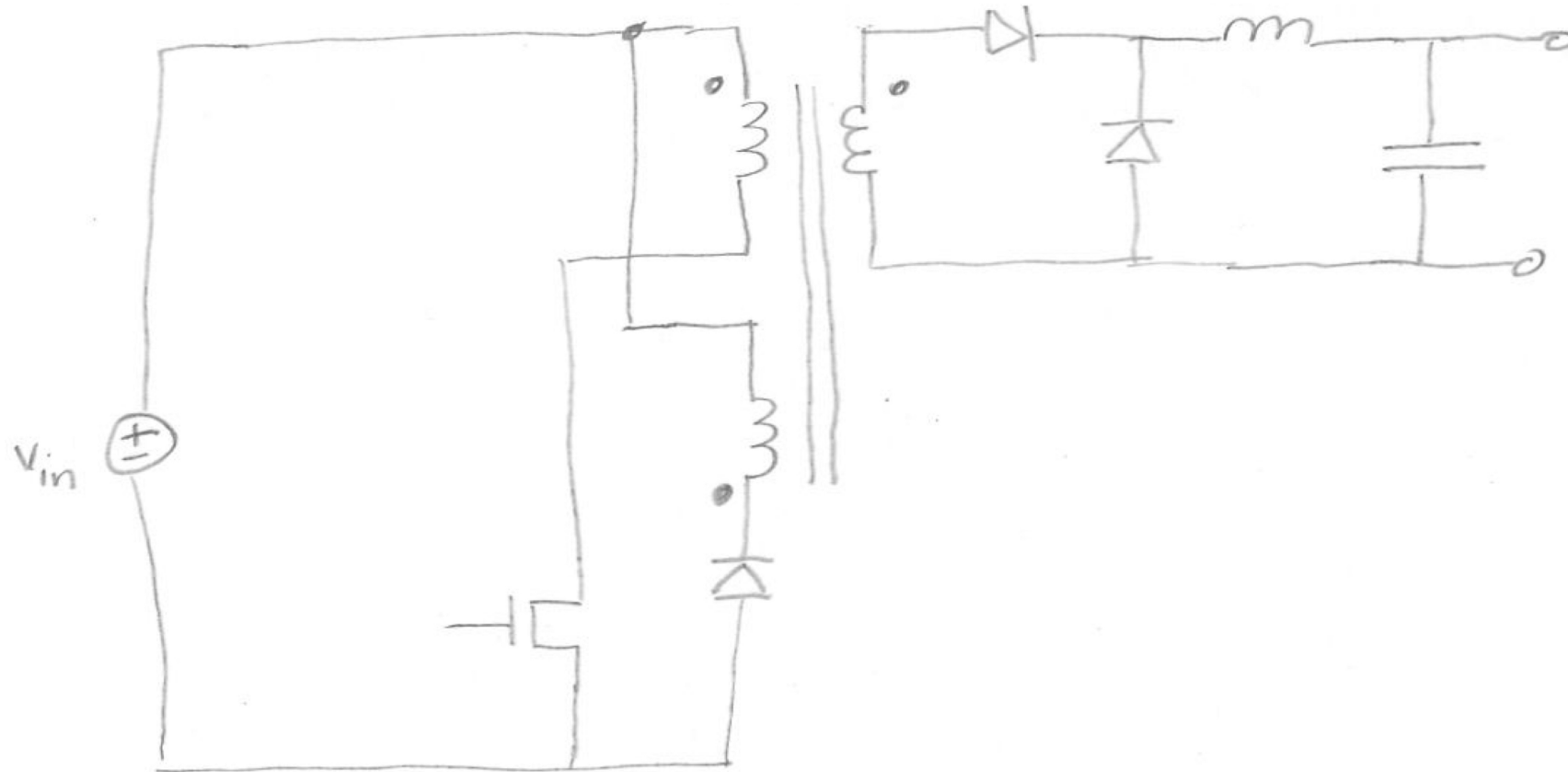
```
.ic v(D) 160
```

```
.ic I(LP) 0
```

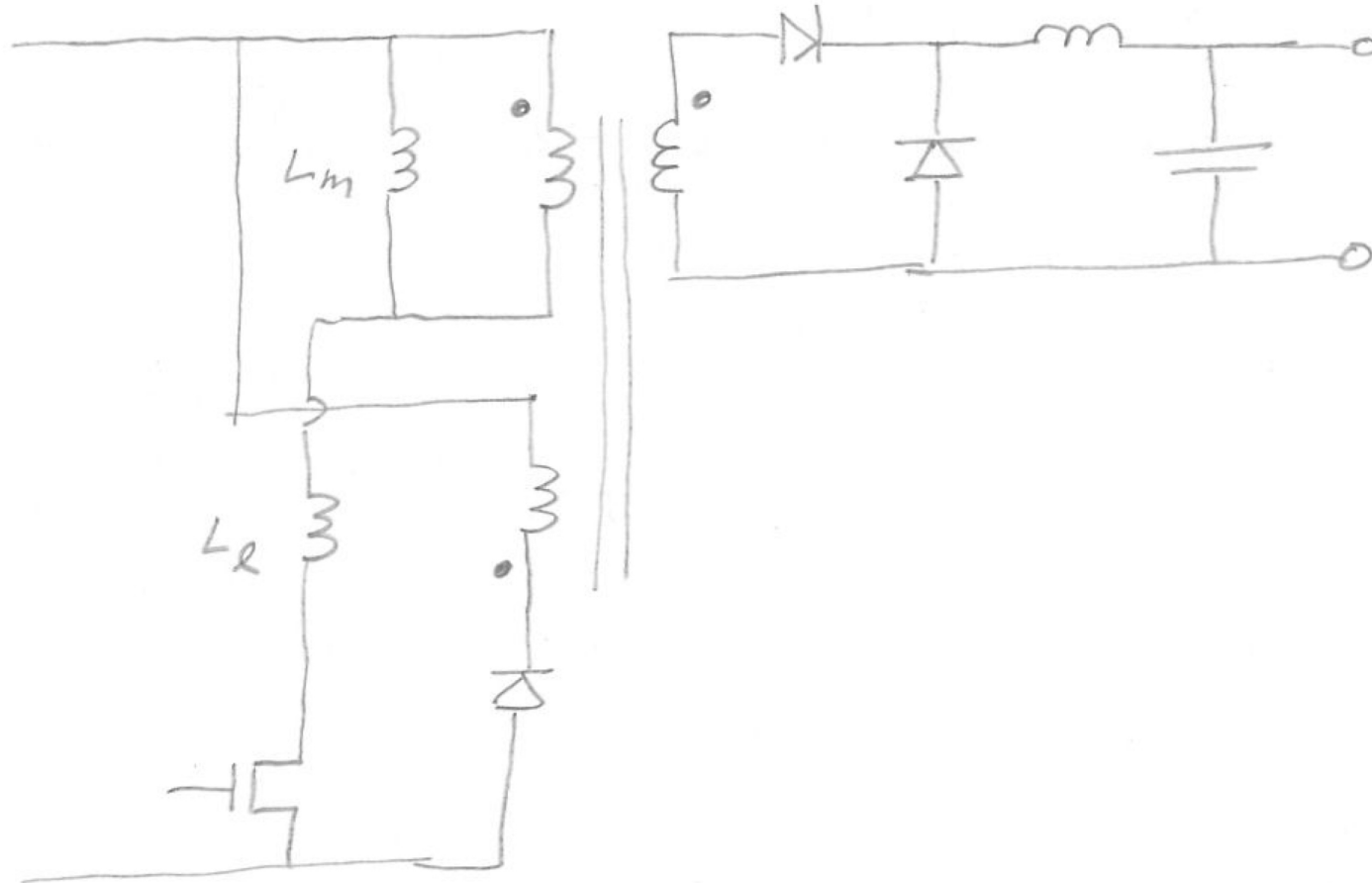
```
.ic I(LPM) 0
```

```
.tran {Tcy*Ncy}
```

# Forward Converter



# Forward Converter With $L_m$ and $L_l$

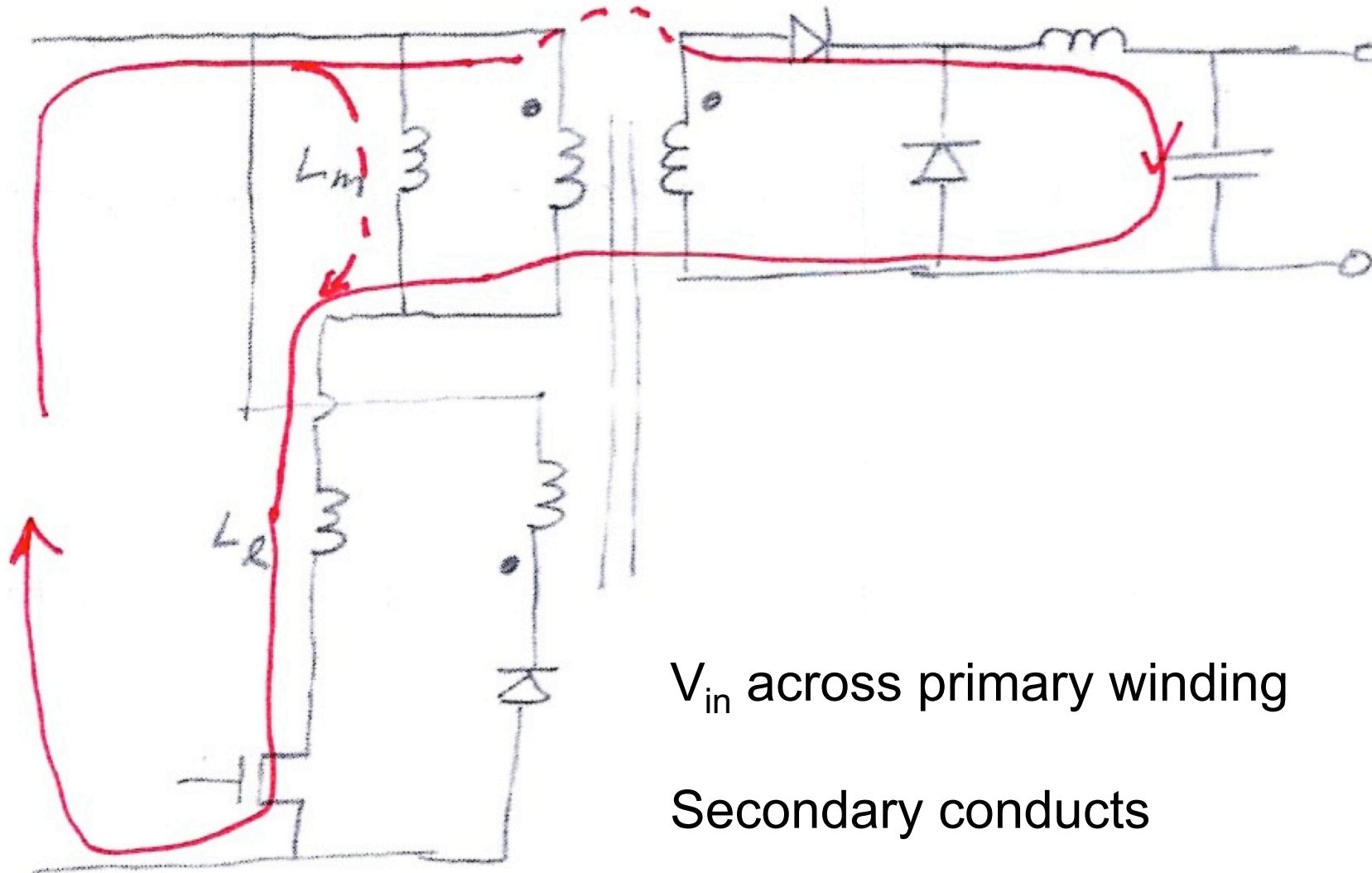


# Forward Converter Operation

## Phases

1. Primary current ramps in  $L_L$  (secondary shorted)
2. Primary and secondary conduct ( $V_{in}$  across primary)
3. Secondary current switches (secondary shorted)
4. Recovery of  $L_M$  energy ( $-V_{in}$  across recovery wdg)
5. Off

# Forward Phase

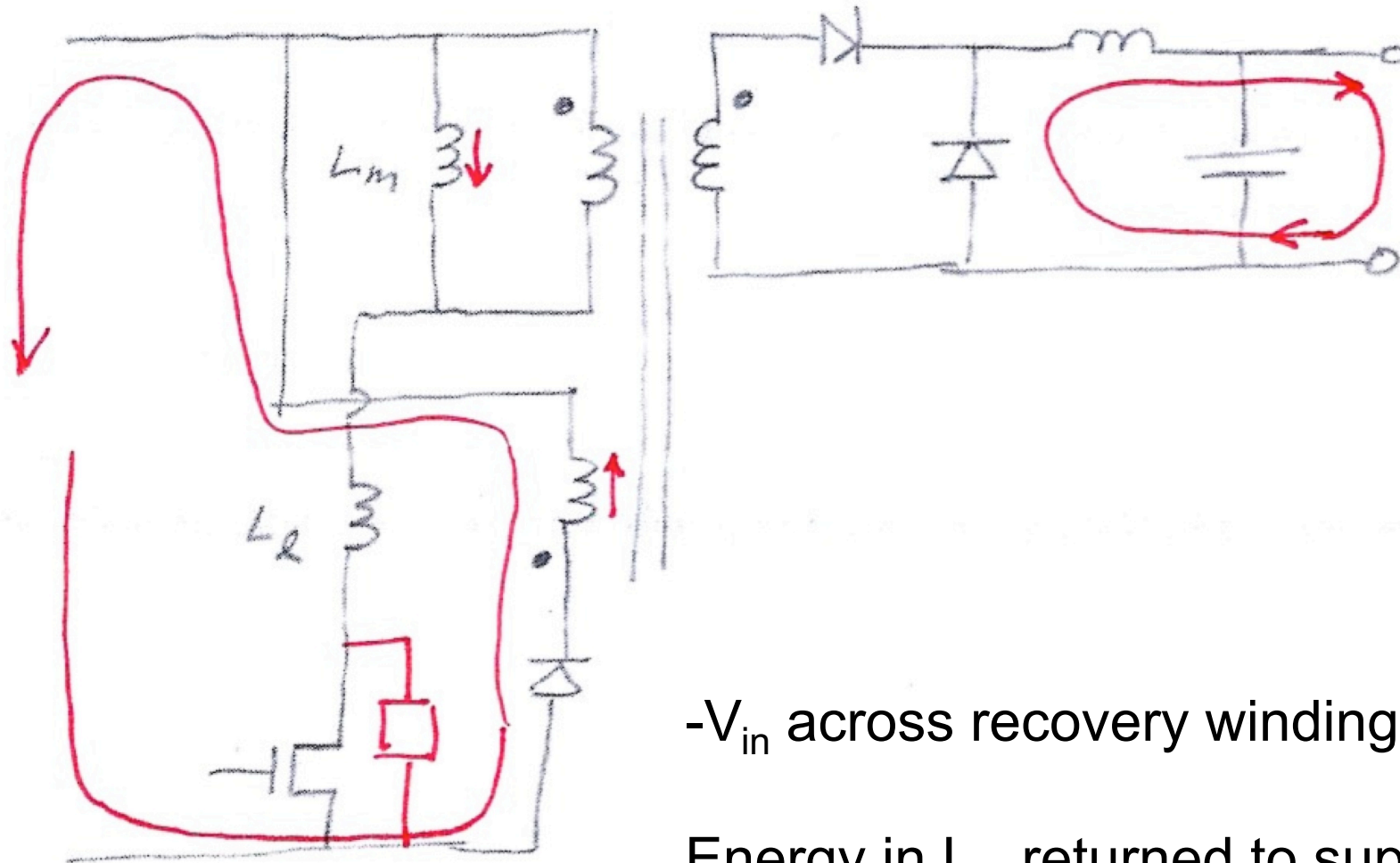


$V_{in}$  across primary winding

Secondary conducts

Energy stored in  $L_m$

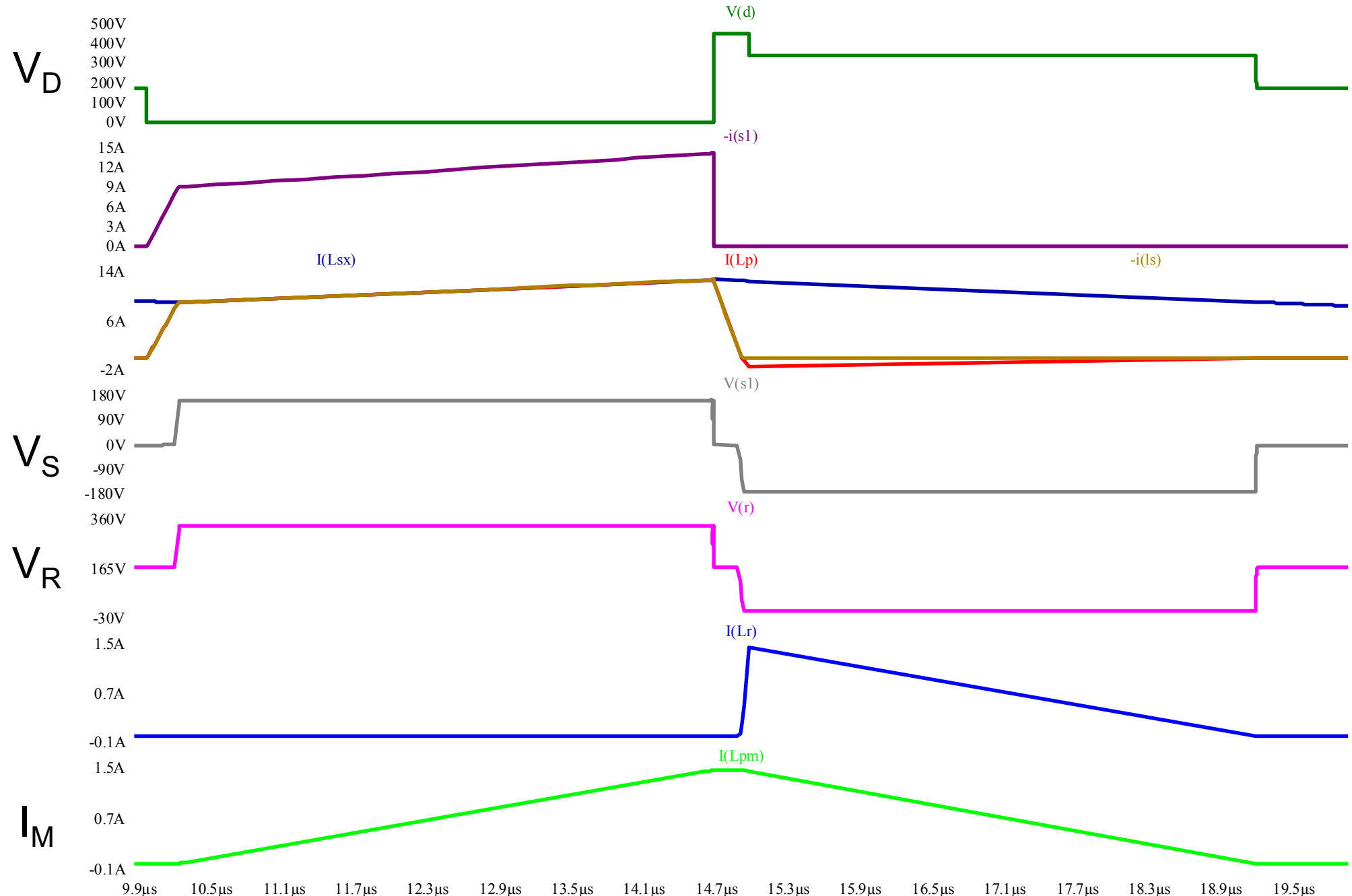
# Recovery Phase



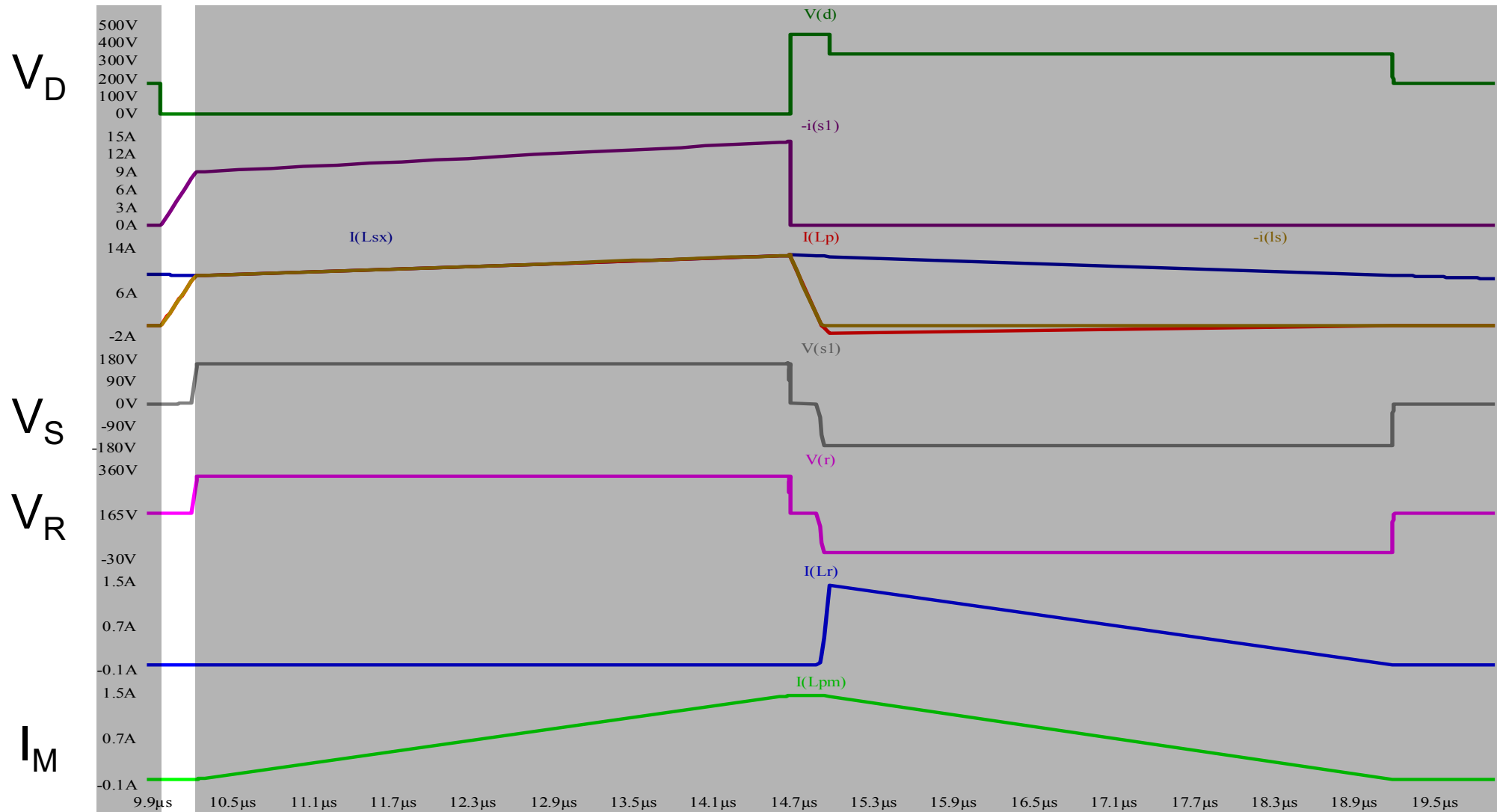
$-V_{in}$  across recovery winding

Energy in  $L_m$  returned to supply

# Forward Converter SPICE



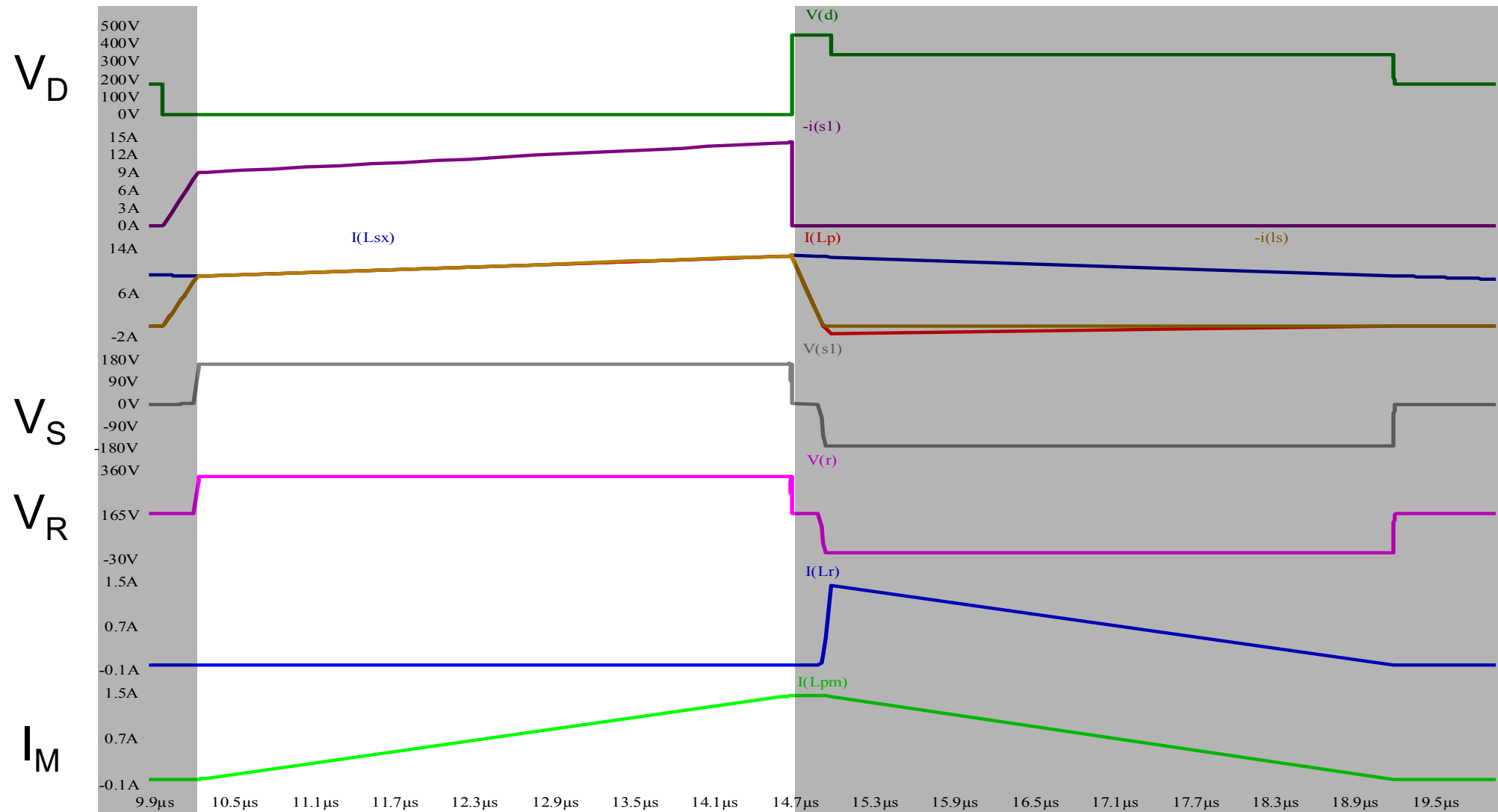
Interval 1: **Commutation – on**  
Drain drops to ground  
Current ramps up in leakage inductance



# Interval 2: Drive

Drain drops to ground

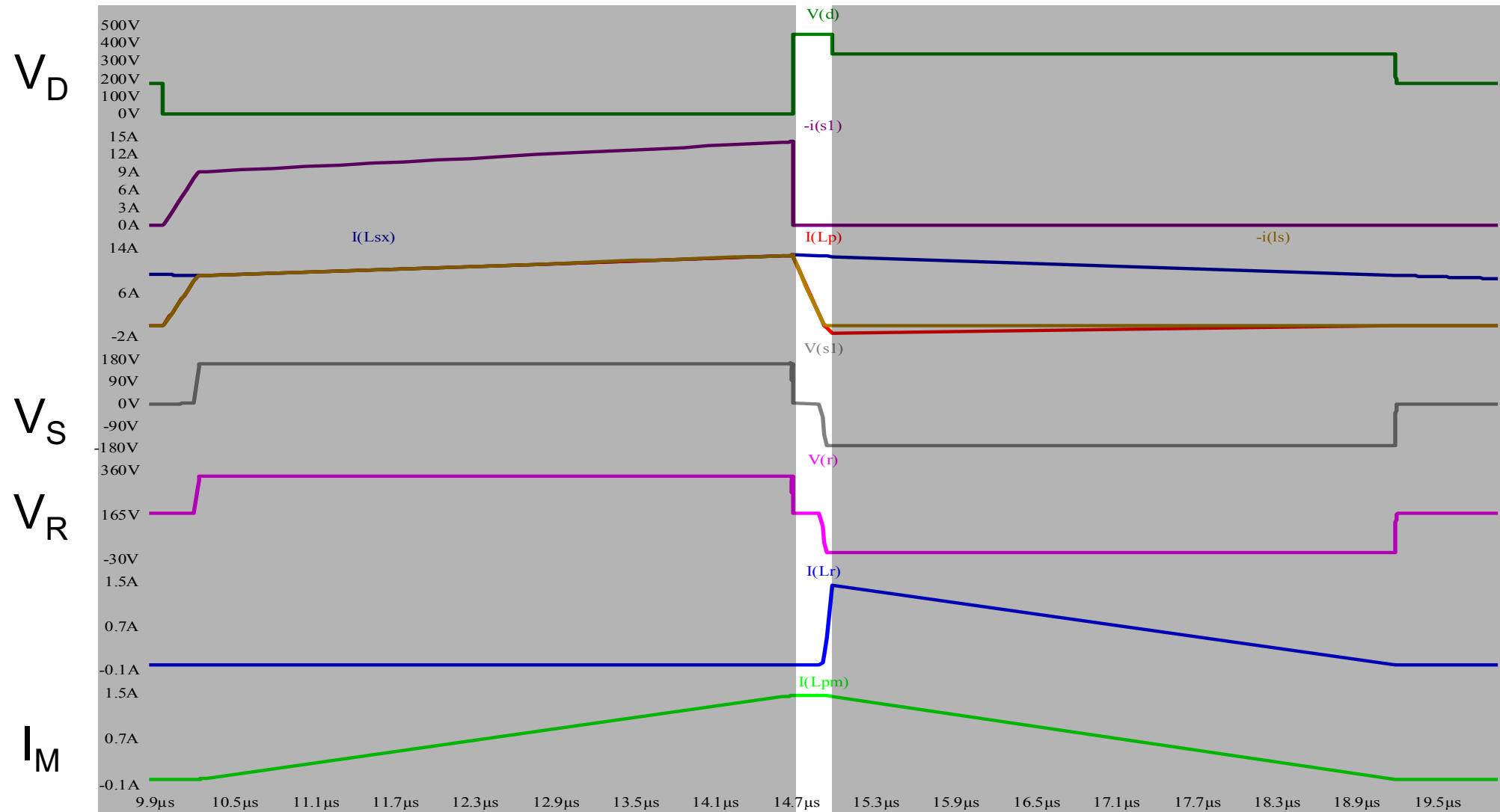
Current ramps up in output inductor



# Interval 3: Commutation - off

Drain rises to “clamp” voltage

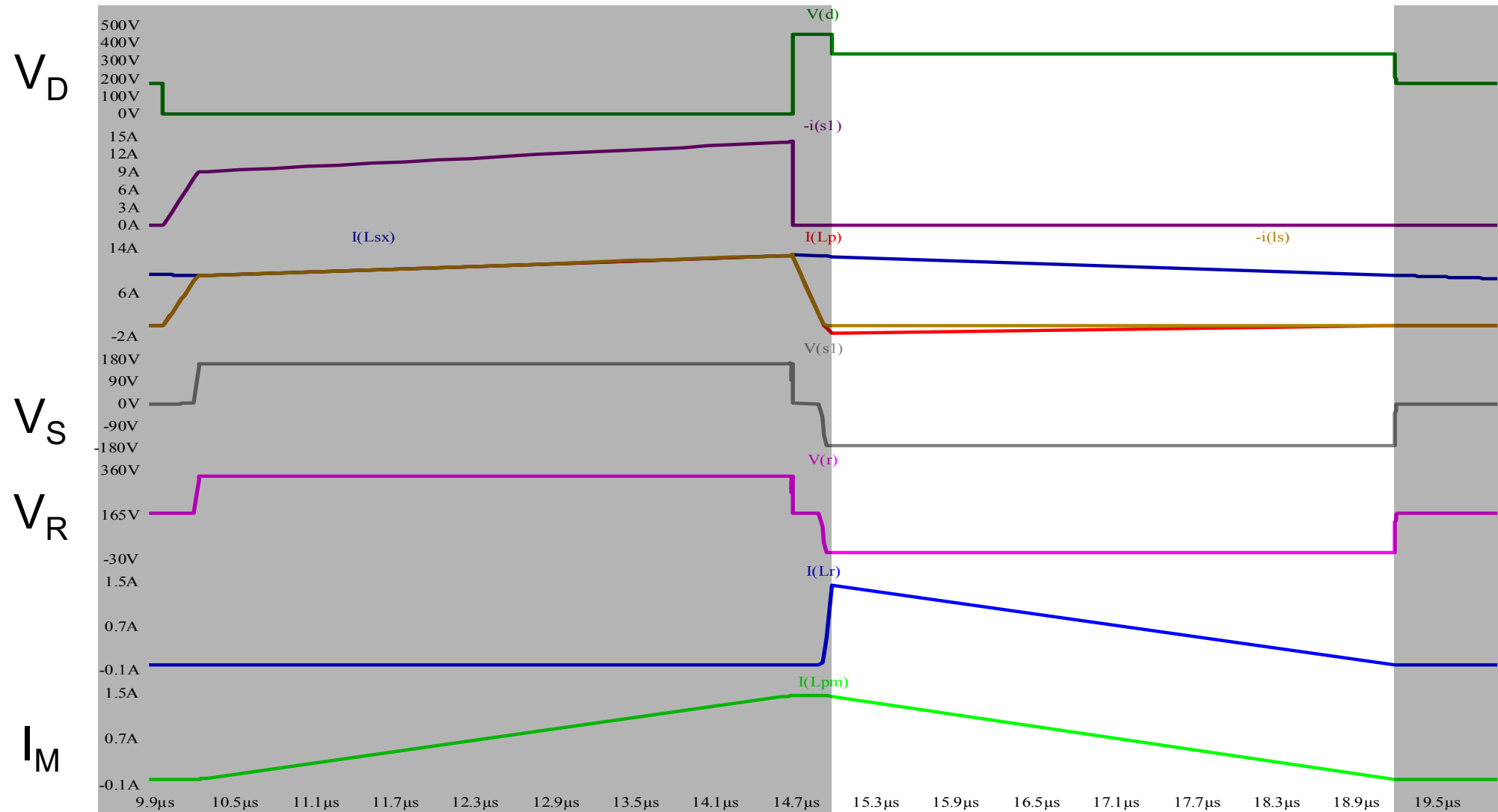
Current ramps down in leakage inductance



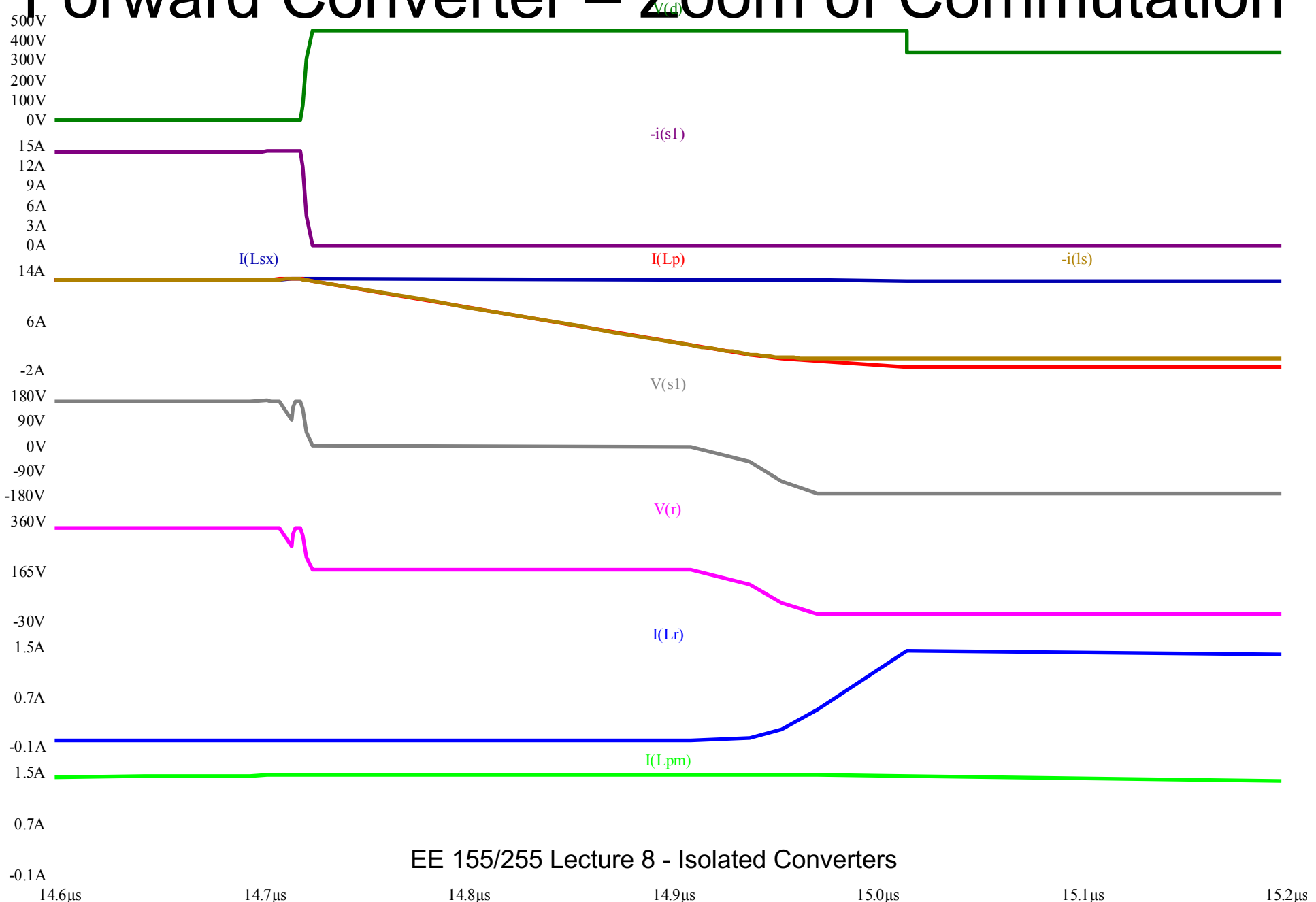
# Interval 4: Recovery

Supply voltage across recovery winding

Current ramps down in magnetizing inductance

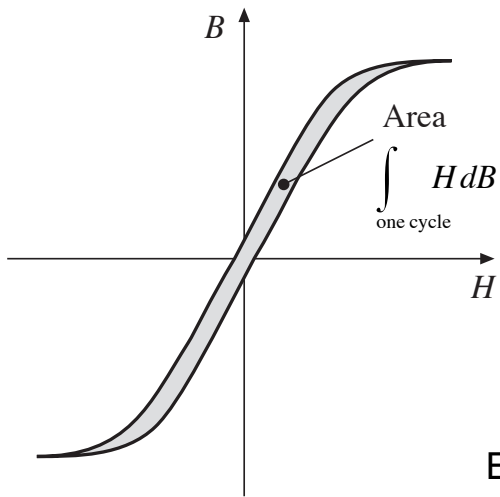


# Forward Converter – Zoom of Commutation

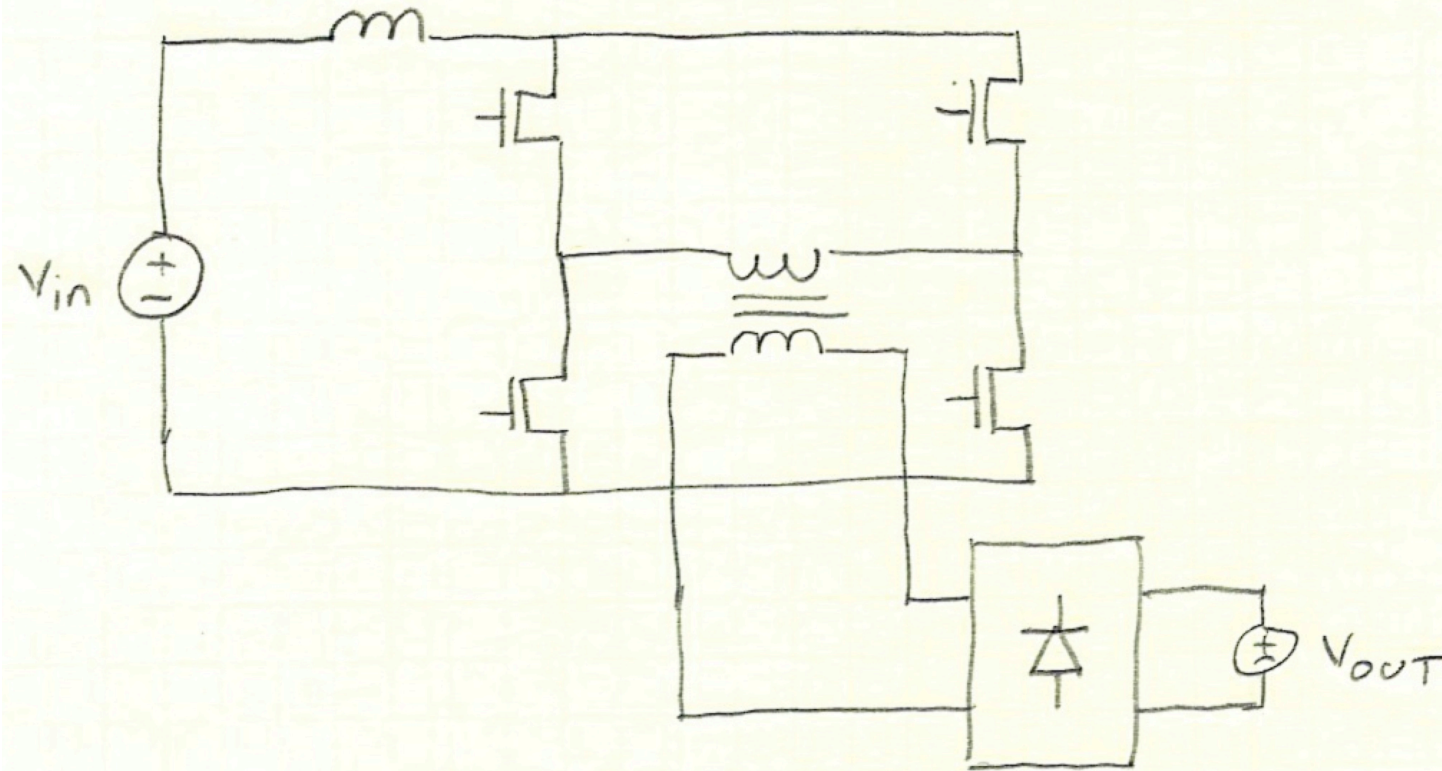


# Using the B-H Curve

- Flyback and Forward converters only use half the B-H curve
- Also, each winding conducts only half the time
- Thus, they require larger magnetic components per unit power than would otherwise be required
- Bridge converters use the whole B-H curve and can conduct much of the cycle



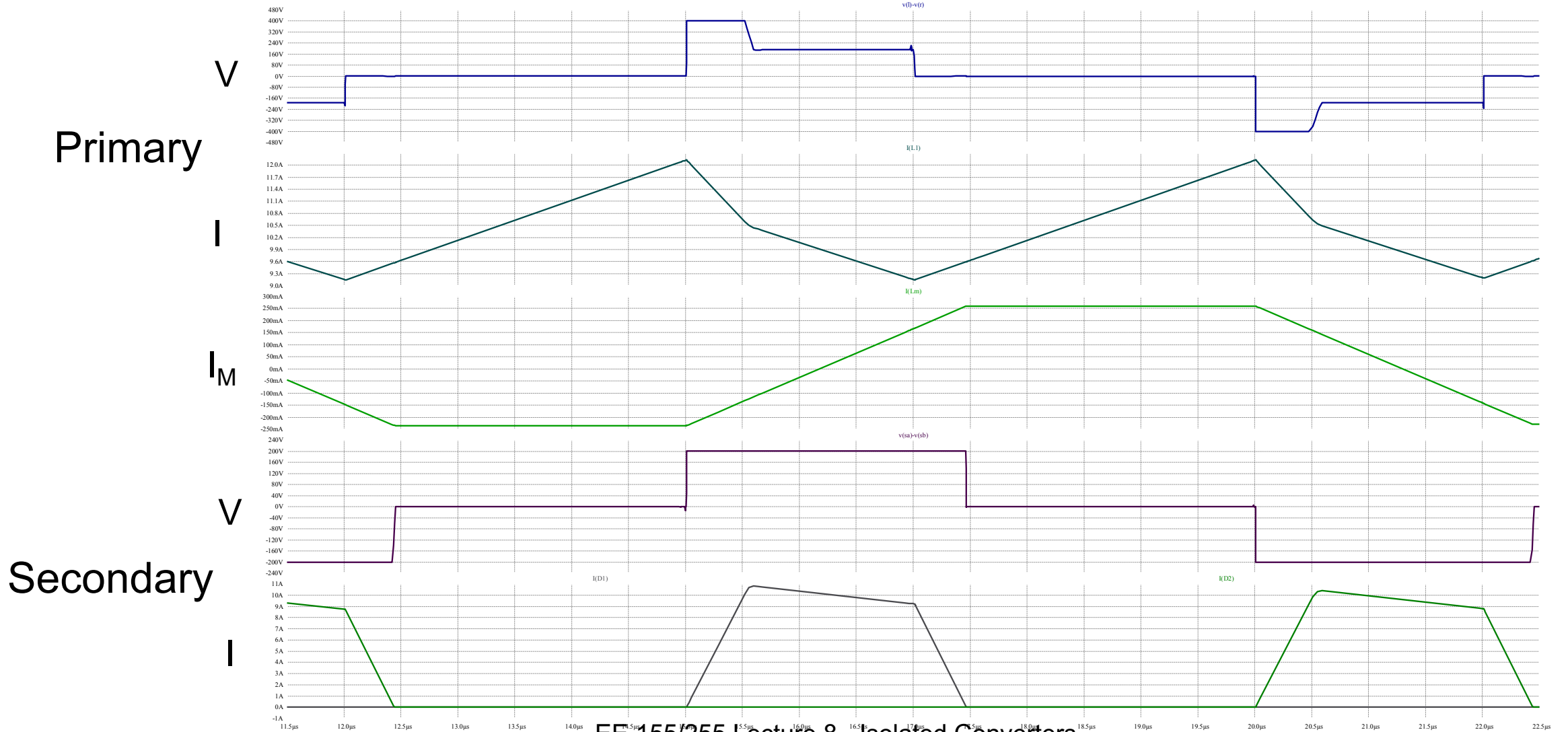
# Current-Fed Bridge



# Current-Fed Bridge Operation

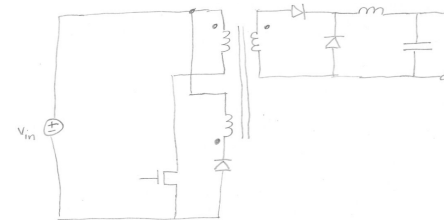
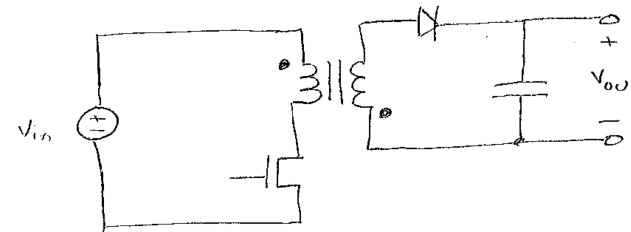
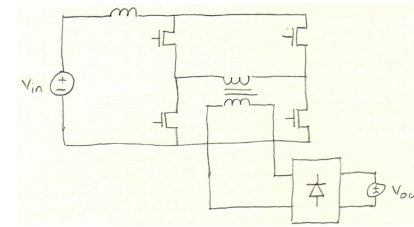
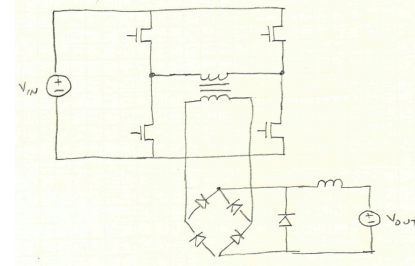
1. All four switches on
  - $V_{in}$  across input inductor – current increases
  - Primary shorted
  - Output open
2. UR and LL on
  - $V_{in} - NV_{out}$  across input inductor – current decreases
  - $V_{out}$  across secondary
  - Current delivered to output
3. All four switches on (like 1)
4. UL and LR on (like 2 but)
  - $-V_{out}$  across secondary

# SPICE Waveforms for Current-Fed Bridge



# Summary of Isolated Converters

- Transformer
  - For galvanic isolation or high step-up/step-down ratio
  - Ideal transformer
  - Magnetizing and Leakage inductance (set speed range)
  - Need to provide volt-seconds balance
- Bridge
  - Buck (boost) with transformer on input (output)
  - Uses the entire B-H Curve
  - Primary drives secondary side inductor on two phases
  - Leakage energy returned to supply via body diodes
- Flyback
  - Uses one side of B-H curve
  - Magnetizing inductance used to store energy
  - Leakage energy dumped to drain clamp
- Forward
  - Buck converter with isolation
  - Primary drives secondary-side inductor in one phase
  - Magnetizing current returned to supply in recovery phase



YAH →

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Guest Lecture						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						