Topology Swapping for Switchers

- Sanjaya Maniktala

for :

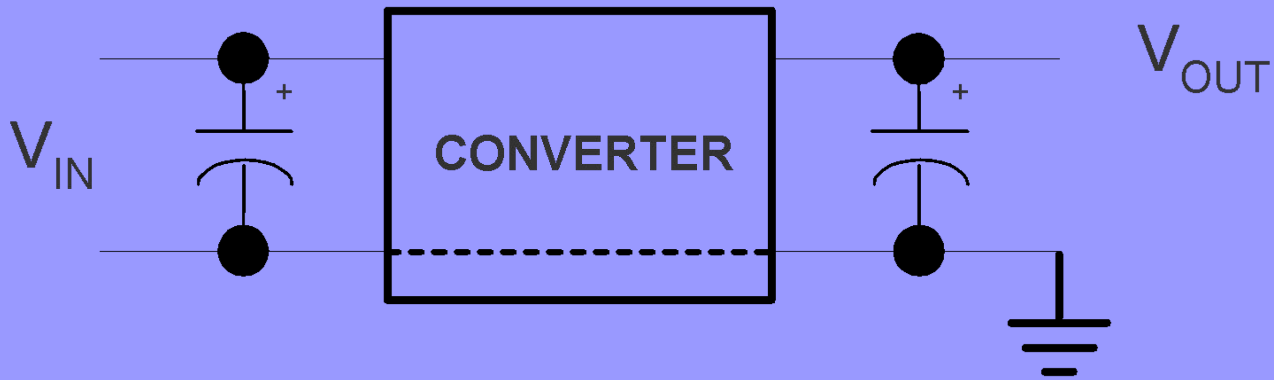
Switching Power Supplies A to Z

A Switcher is a Switcher is a Switcher

A switcher IC is basically this:

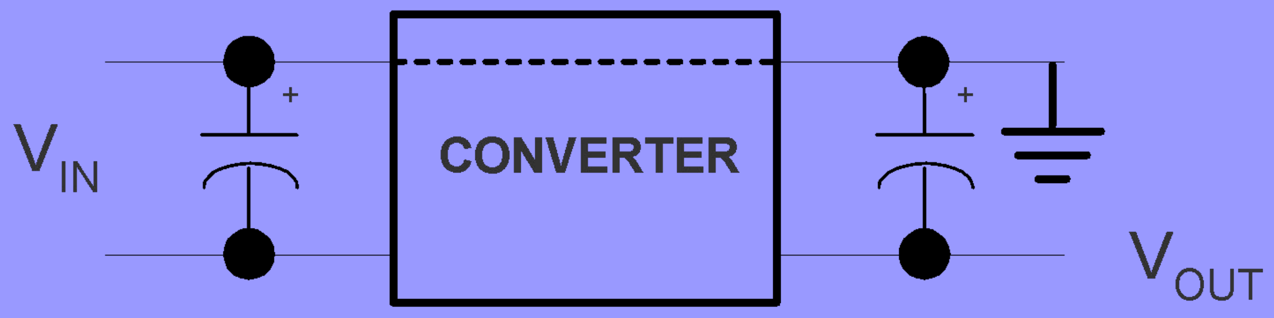
- A switch (Fet or Bipolar)
- A diode (for freewheeling and transferring energy to the output)
- An inductor for energy storage during the process
- Input and Output Capacitors

Understanding what is 'Ground' (+ve to +ve Configuration)



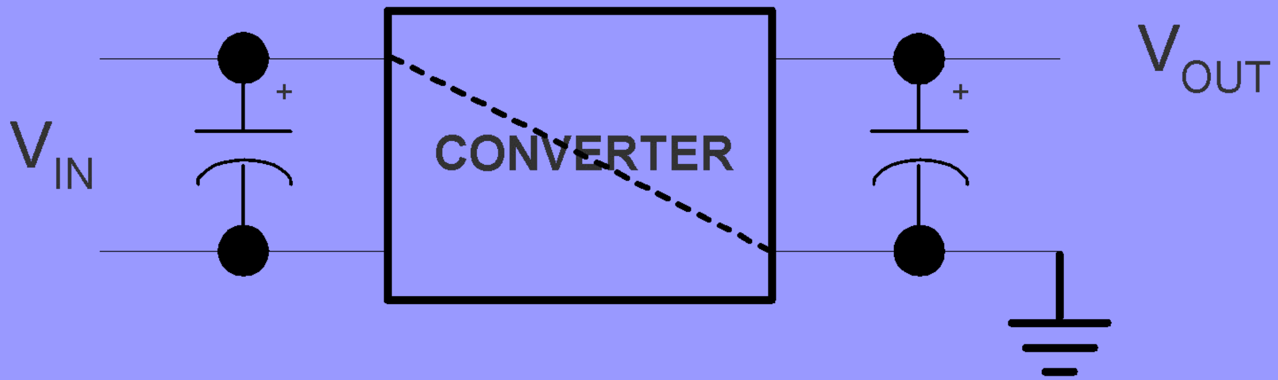
POSITIVE TO POSITIVE CONFIGURATION

-ve to -ve Configuration



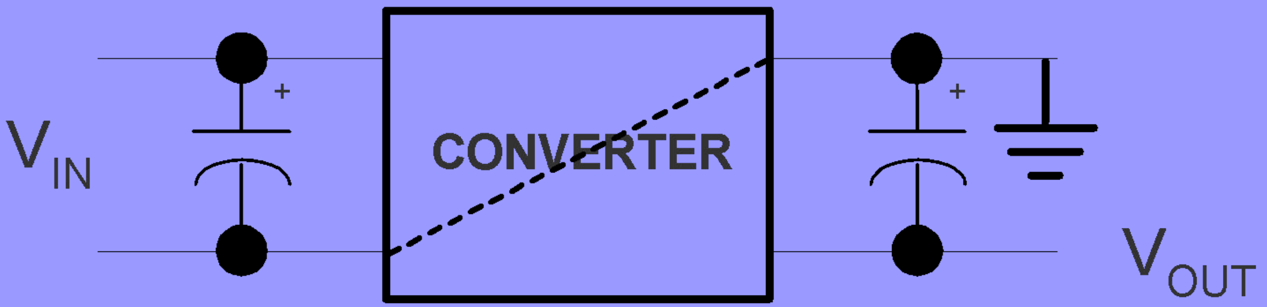
NEGATIVE TO NEGATIVE CONFIGURATION

-ve to +ve Configuration



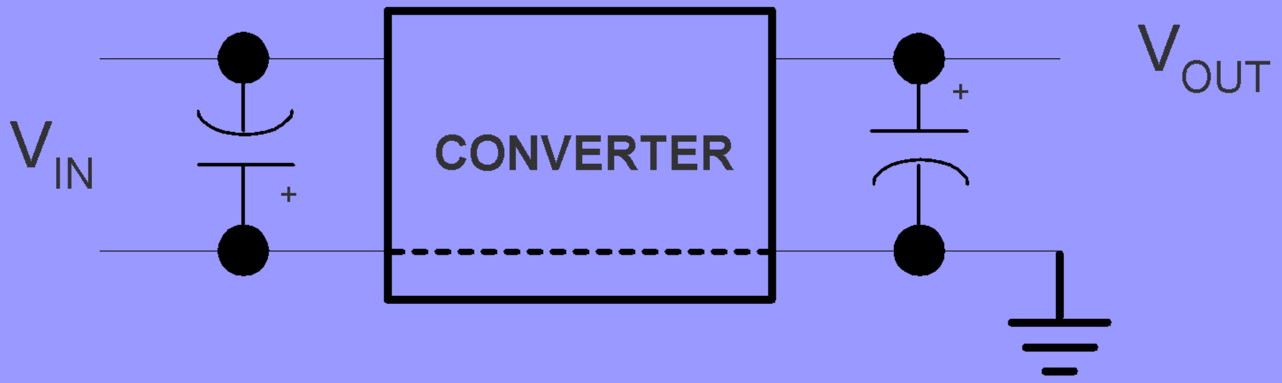
NEGATIVE TO POSITIVE CONFIGURATION

+ve to -ve Configuration



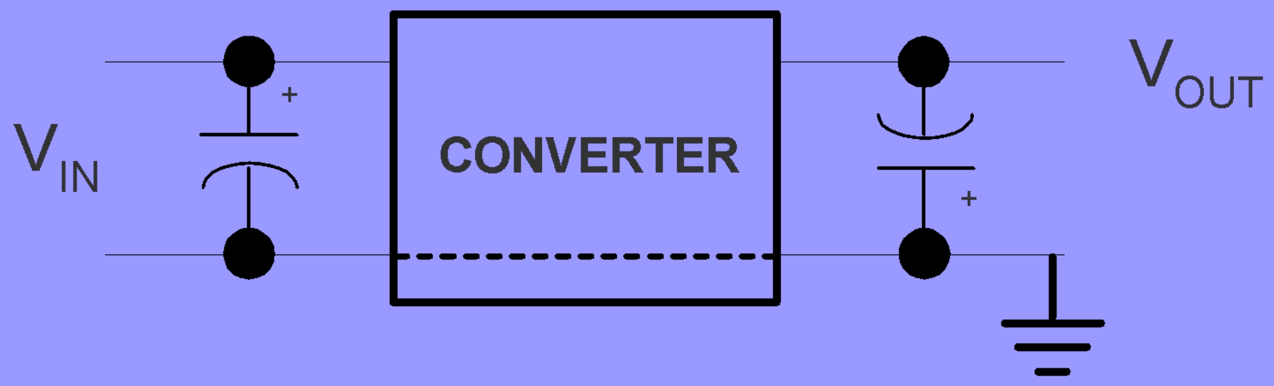
POSITIVE TO NEGATIVE CONFIGURATION

-ve to +ve Configuration (redrawn)



NEGATIVE TO POSITIVE CONFIGURATION

+ve to -ve Configuration (redrawn)



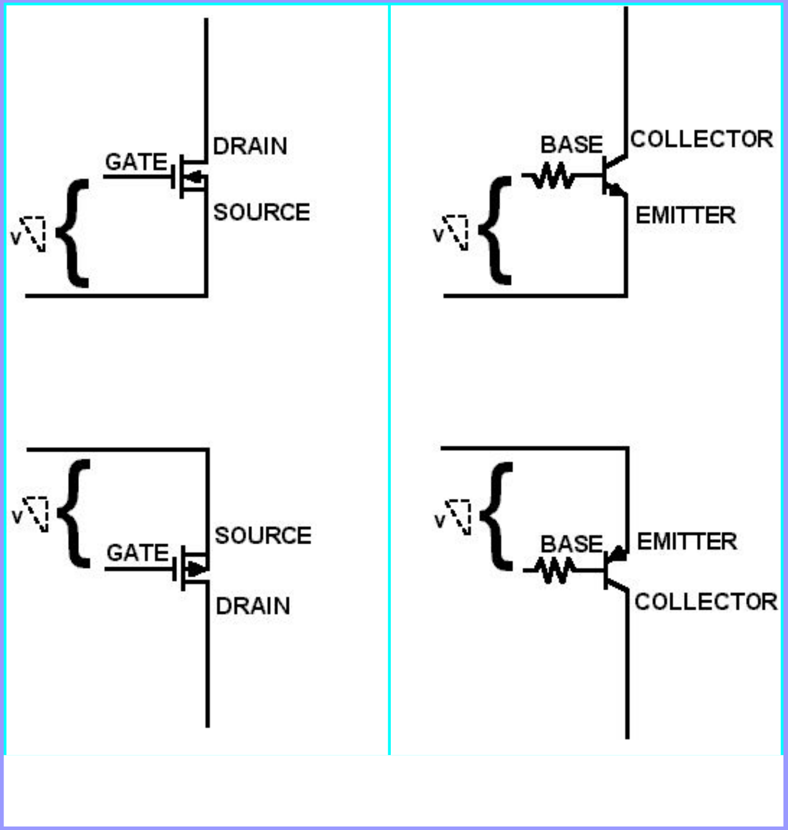
POSITIVE TO NEGATIVE CONFIGURATION

What about the IC Ground?

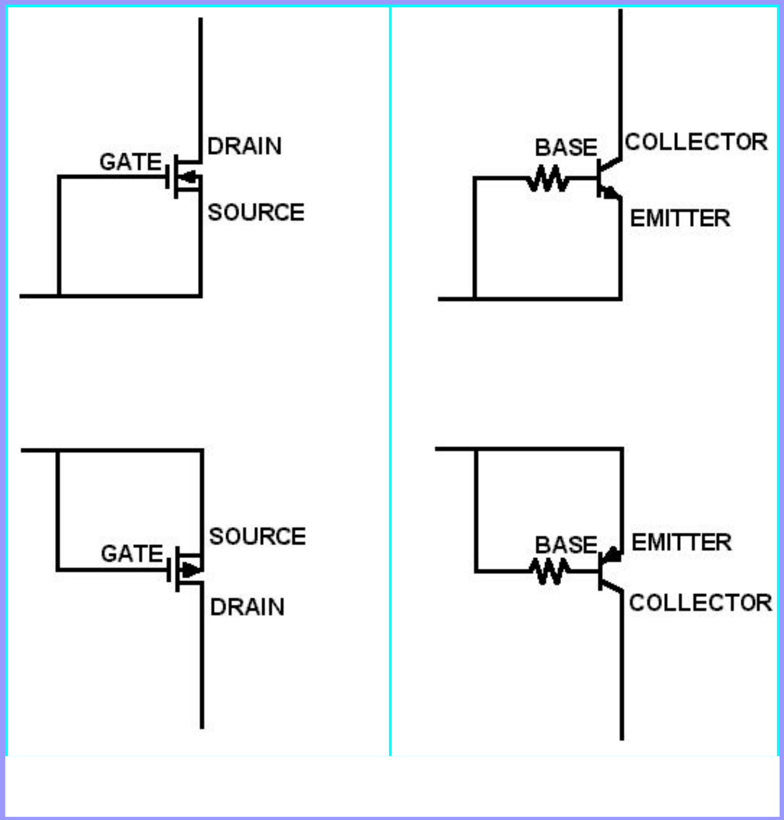
In fact there are so many definitions of ‘Ground’ that it does become confusing. For example we also have the IC (or ‘control’) Ground (sometimes called the ‘analog’ Ground).

In particular, the IC Ground may NOT be the same as the power ground!!

The 'N-switch' and the 'P-switch'
Turning it ON

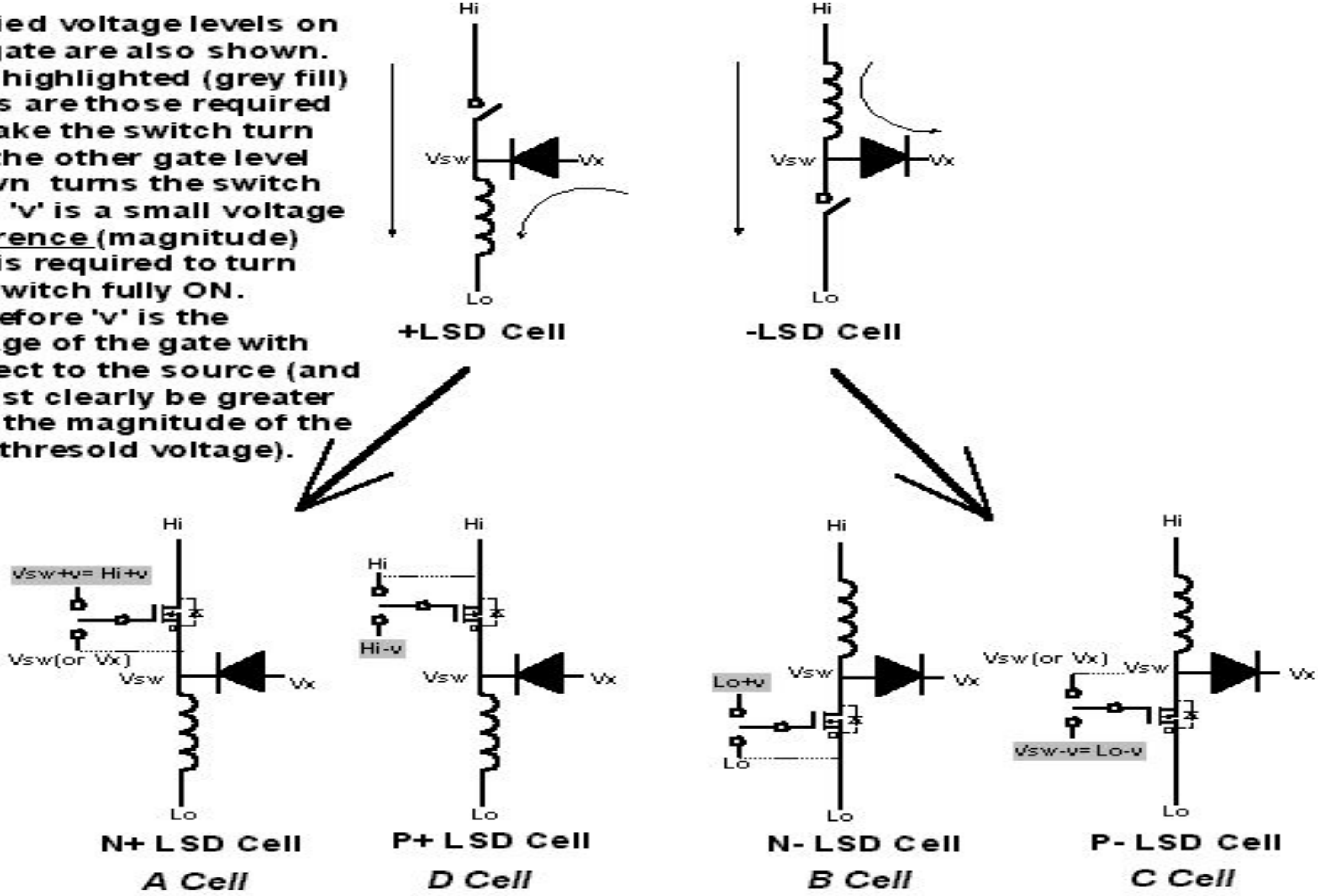


The ‘N-switch’ and the ‘P-switch’ Turning it OFF



The 'LSD' Cell

Applied voltage levels on the gate are also shown. The highlighted (grey fill) levels are those required to make the switch turn ON, the other gate level shown turns the switch OFF. 'v' is a small voltage difference (magnitude) that is required to turn the switch fully ON. Therefore 'v' is the voltage of the gate with respect to the source (and it must clearly be greater than the magnitude of the gate thresold voltage).



The terminology

- If the cathode of the diode connects to the LSD node: call it a '+' LSD cell
- If the anode of the diode connects to the LSD node: call it a '-' LSD cell

So,

1. Type A: N+ cell: cathode is LSD node, N-channel FET or NPN BJT
2. Type B :N- cell: anode is LSD node, N-channel FET or NPN BJT
3. Type C : P- cell: anode is LSD node, P-channel FET or PNP BJT
4. Type D : P+ cell: cathode is LSD node, P-channel FET or PNP BJT

Lookup Table for LSD Descriptors

Type	LSD cell
A	N+
B	N-
C	P-
D	P+

Lookup for LSD cell descriptors

What are configurations?

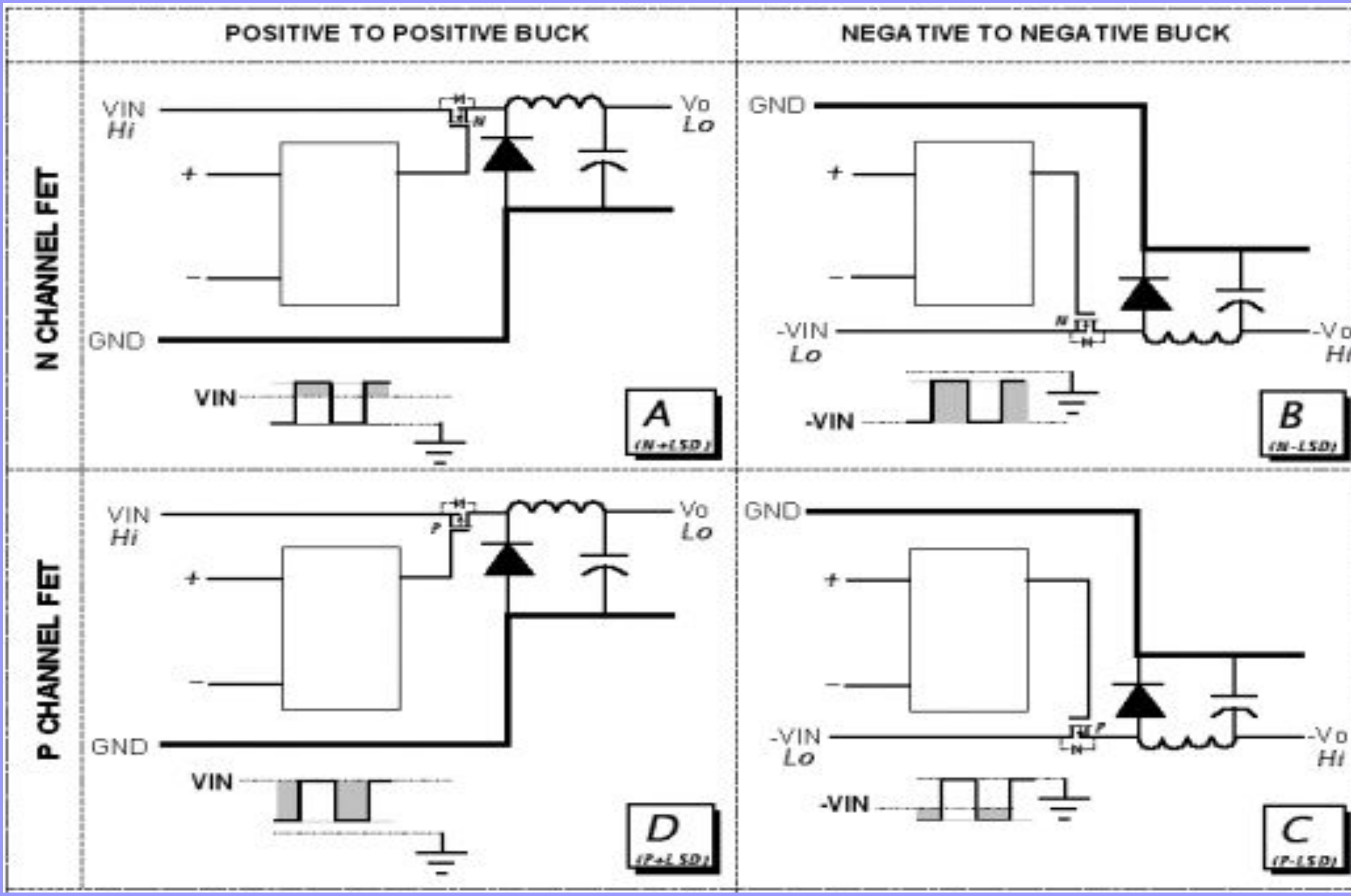
- The words ‘step-down’ (Buck) or ‘step-up’ (Boost) or ‘step up/down’ (Buck-Boost) merely refer to the MAGNITUDES of the input and output voltages. These are therefore TOPOLOGIES.

- But we can have for example a <u>+ve to +ve</u> Buck or <u>–ve to –ve</u> Buck. So the qualifiers are the CONFIGURATIONS

Buck-Boost Configurations

- The Buck-Boost will take a given voltage and change it to either a smaller voltage (Buck) or a larger voltage (Boost) depending on the duty cycle.
- However it can be shown that in the process, the polarity is ALWAYS inverted.
- A topology which can change say +10V to +15V and also do +10V to +5V (at our will) does NOT exist.
- A topology which will invert polarities but just be capable of Bucking or only Boosting, also does not exist.

Buck Configurations



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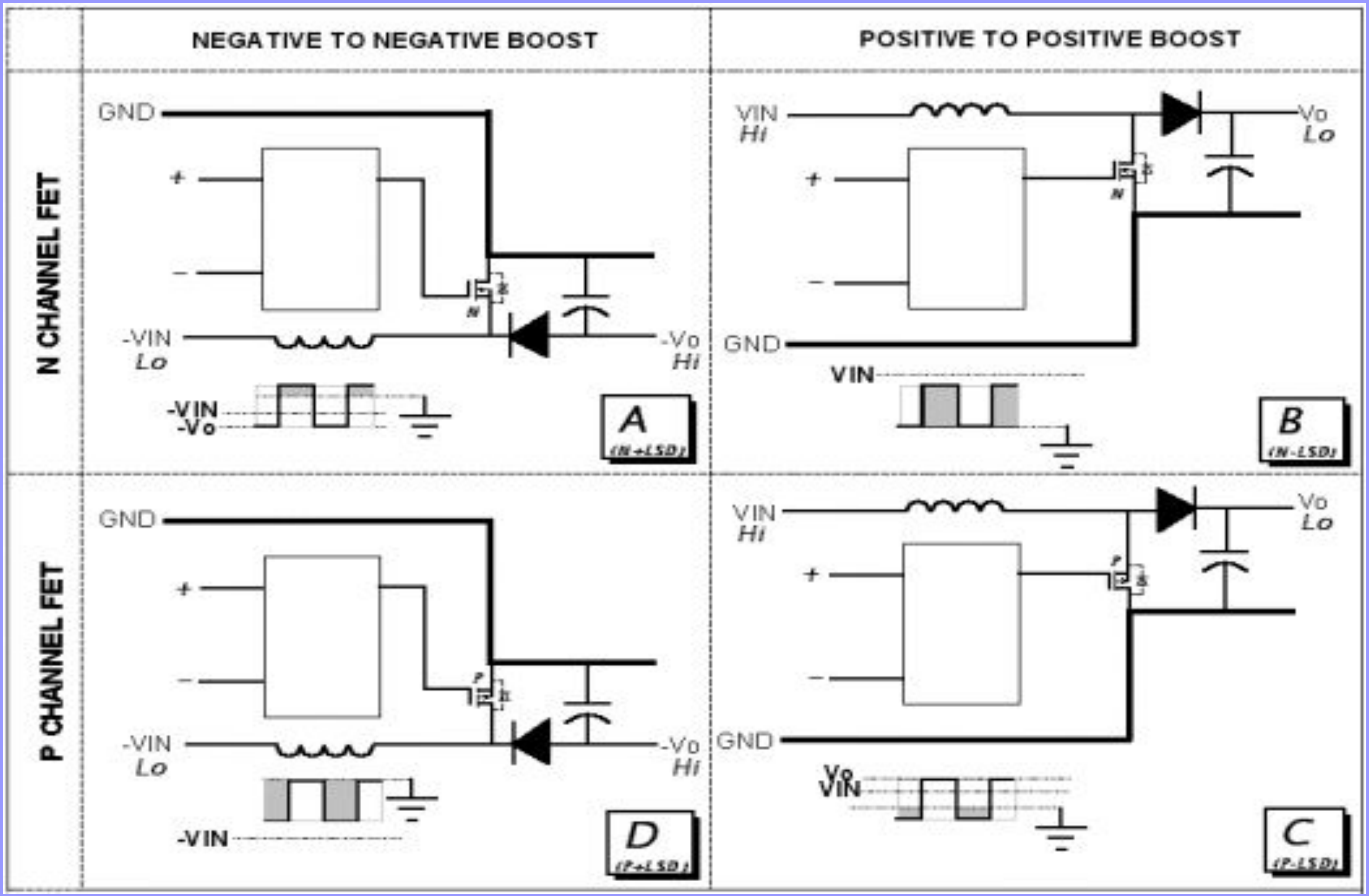
Boost Configurations



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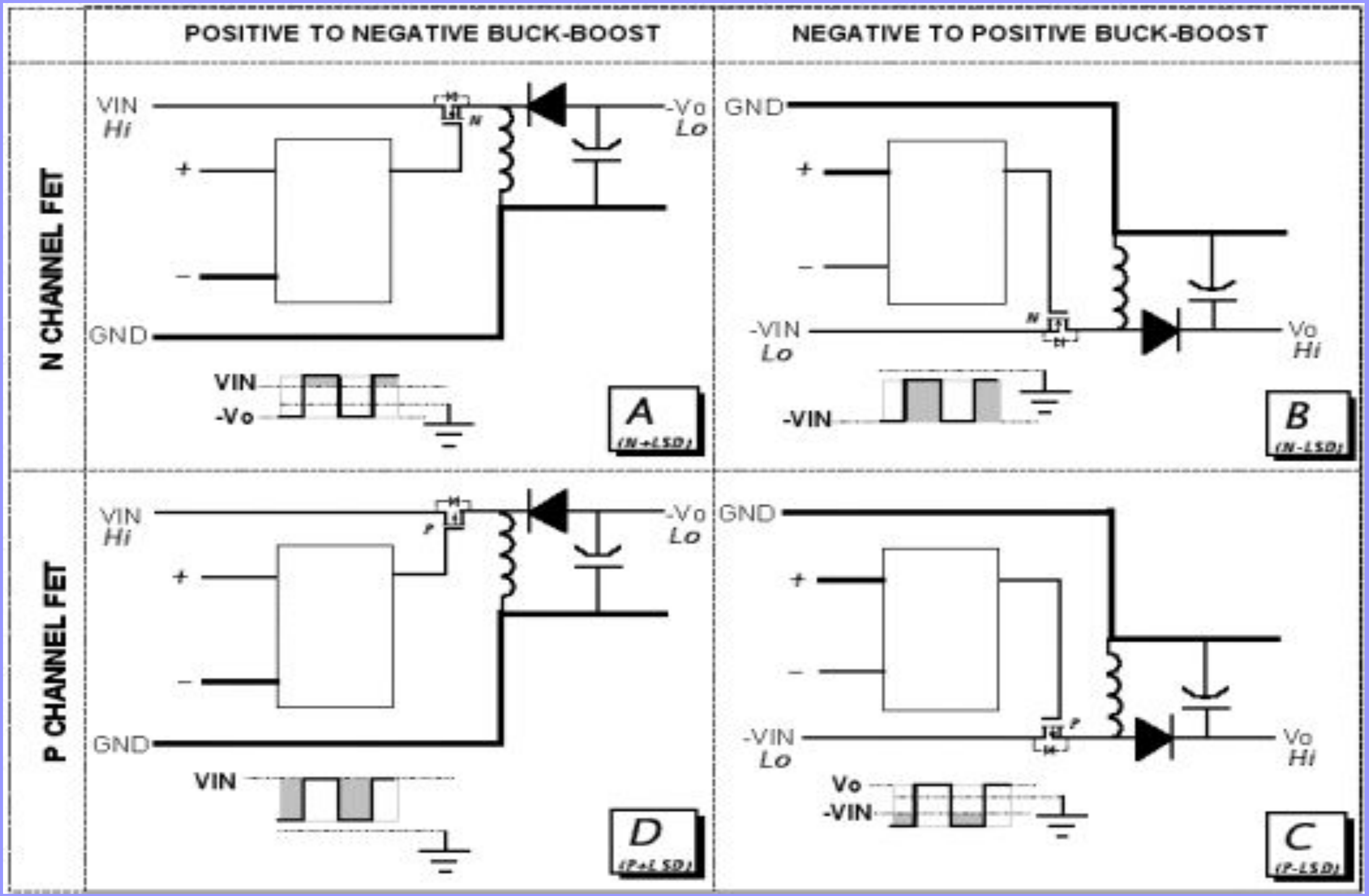
Buck-Boost Configurations



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N-Switch Configurations to P-Switch Configurations

To draw the negative ground circuit from a positive ground circuit (and vice versa) we simply invert all circuit polarities.

'Inversion'

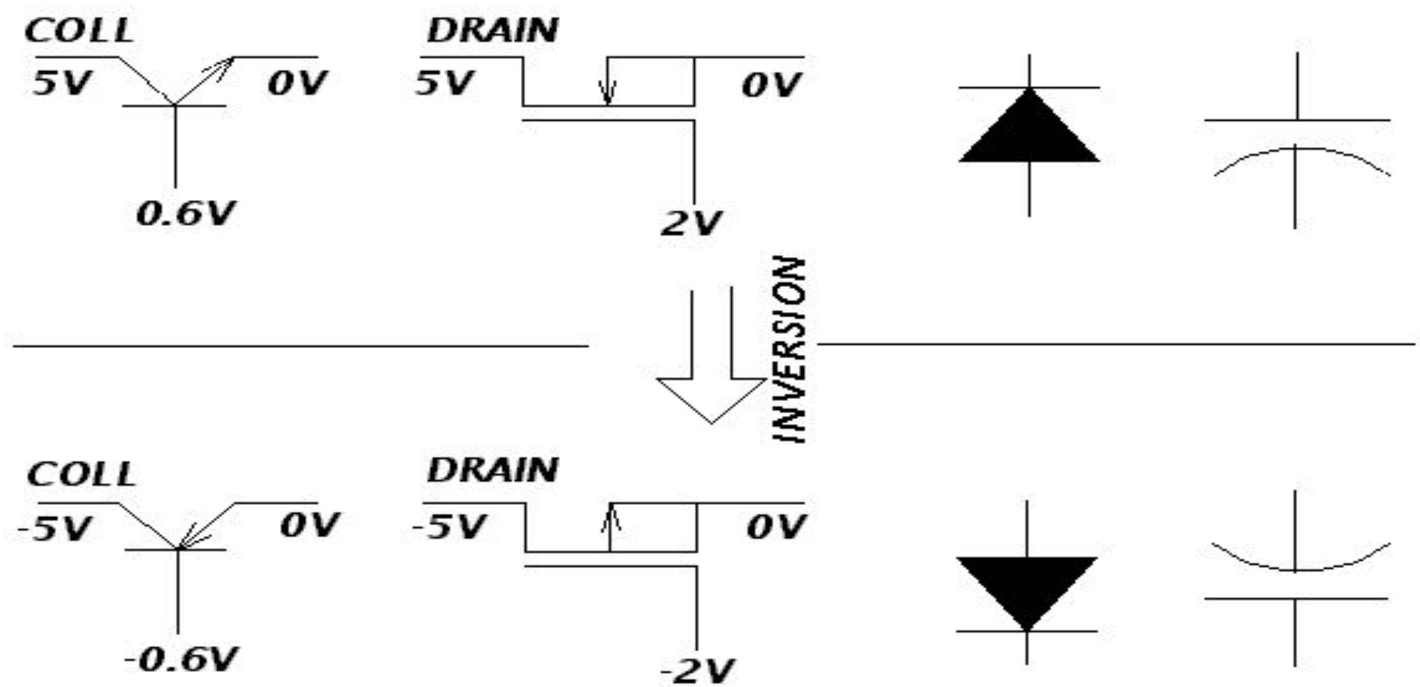
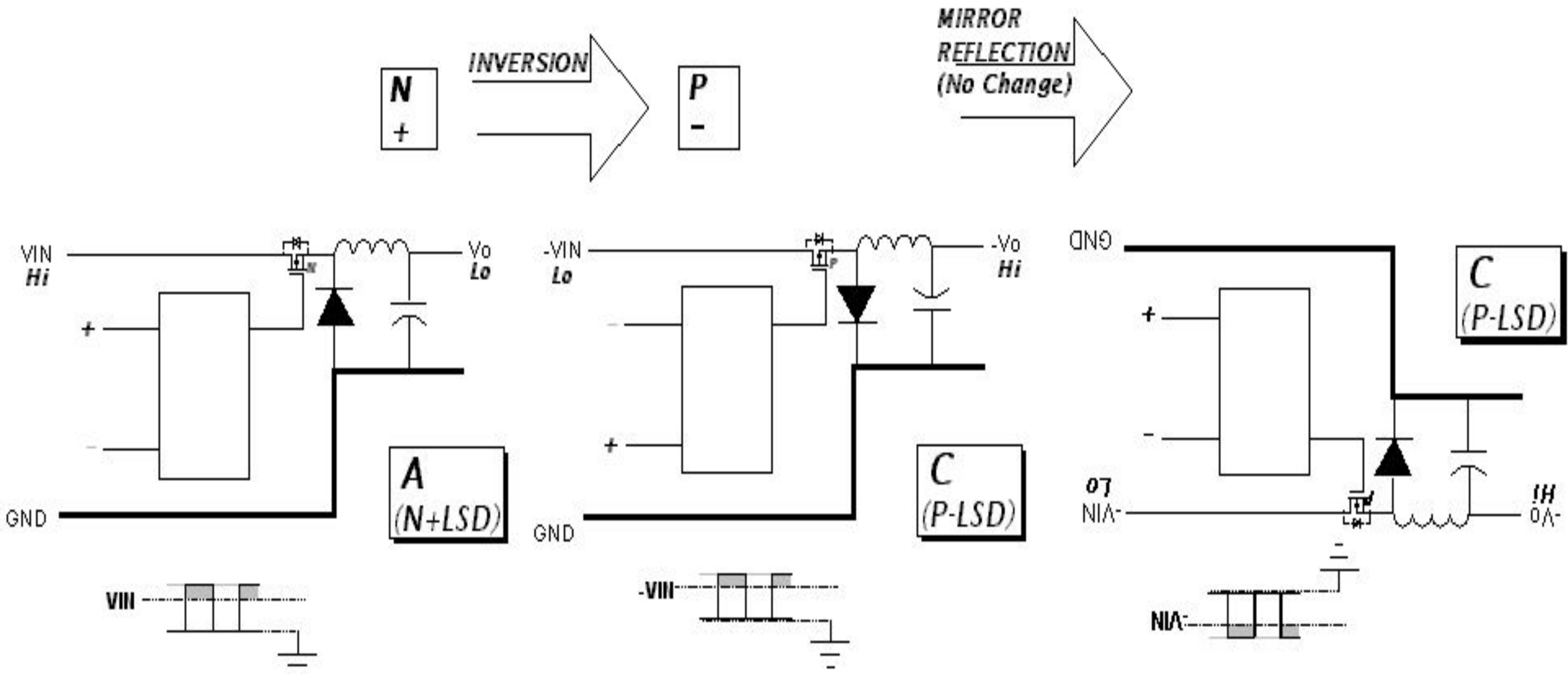


FIGURE 6

An example of 'Inversion'

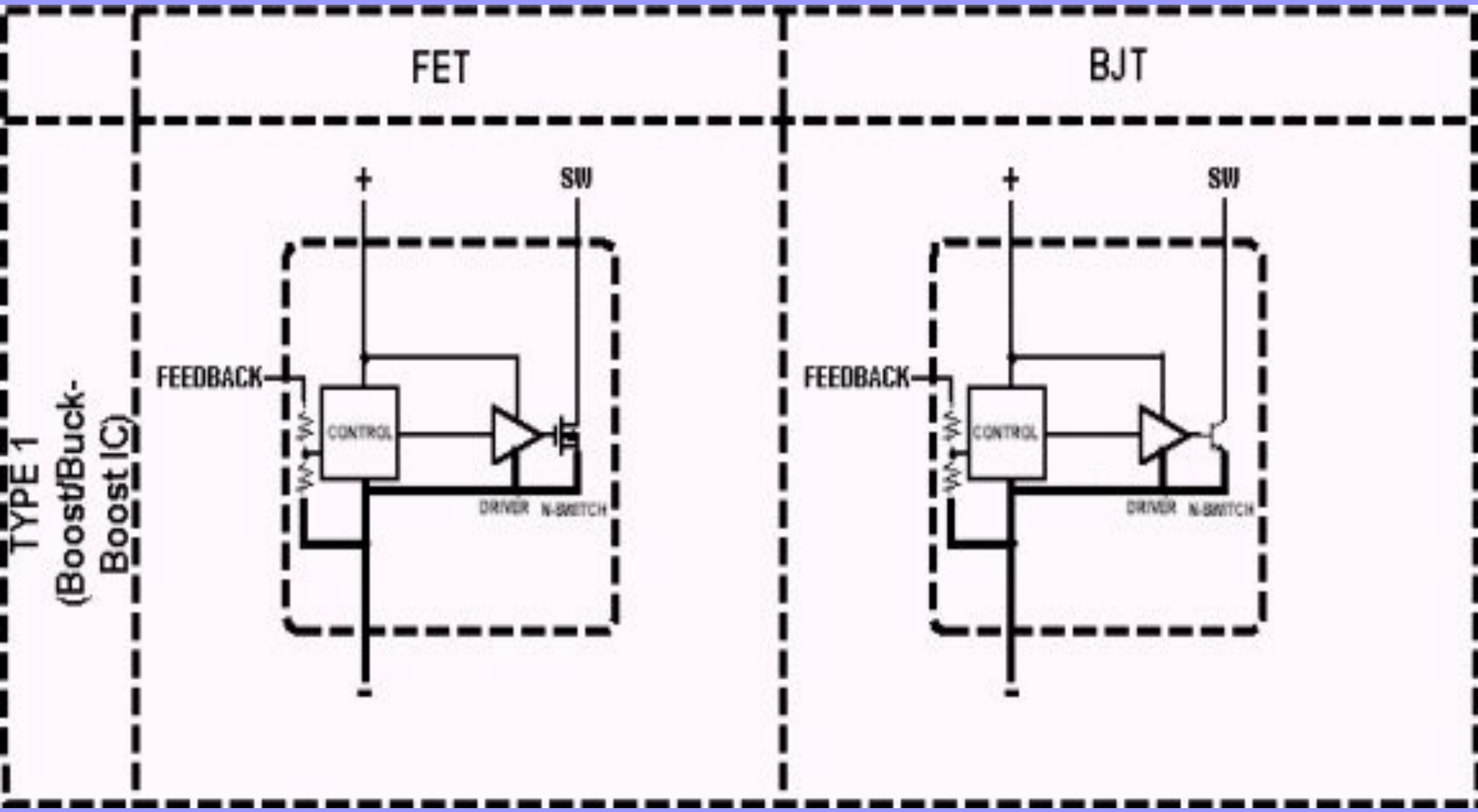


POSITIVE TO POSITIVE BUCK (with N-switch) 'INVERTED' TO GIVE A NEGATIVE TO NEGATIVE BUCK (with P-switch)

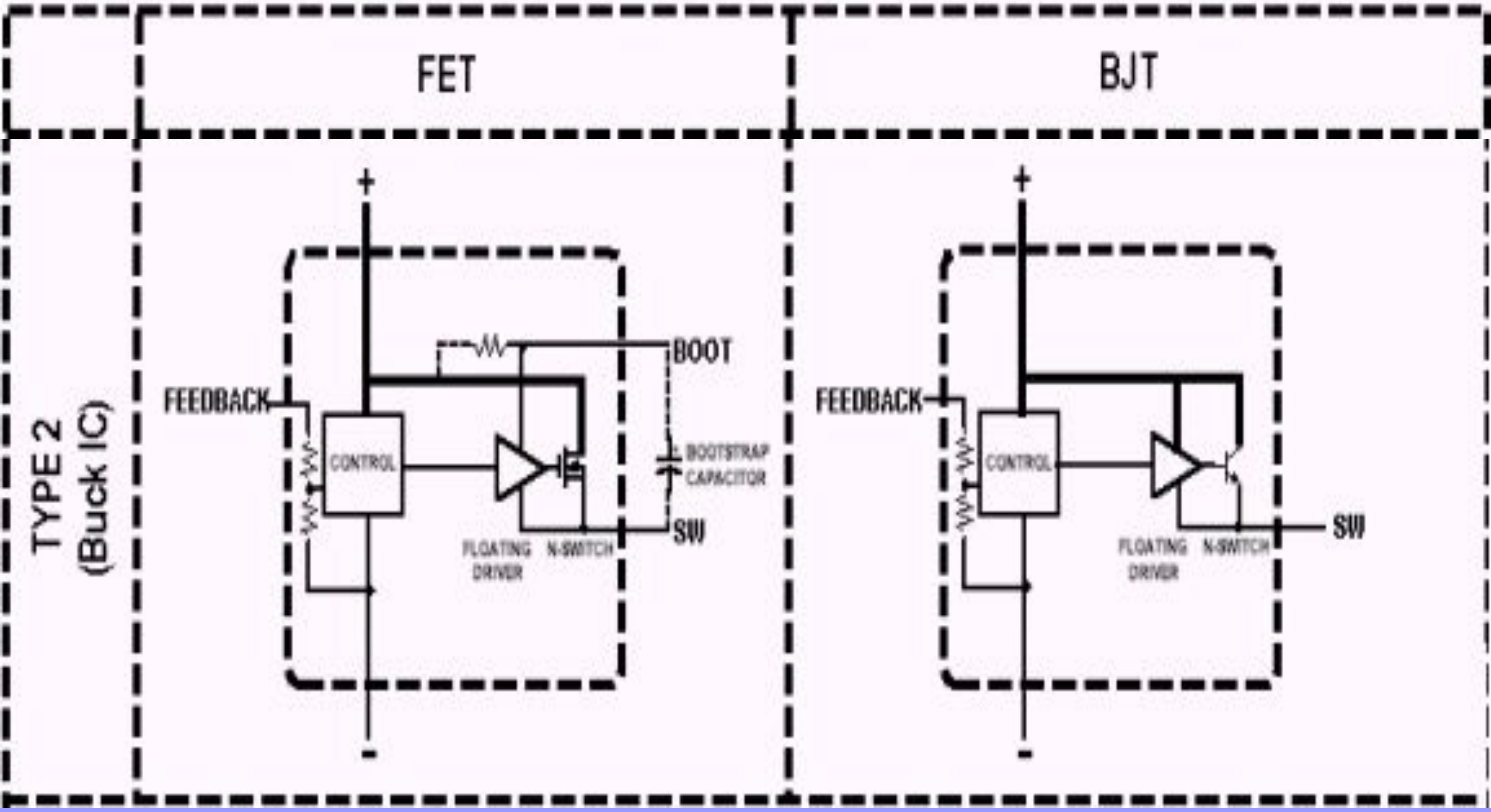
Why study the IC Construction?

Having understood the topologies and their configurations, it is important to also note the internal construction of the switcher IC, so that we can tap its full potential and judge its suitability for a particular topology/configuration.

Type 1 IC ("Boost/Buck-Boost IC")



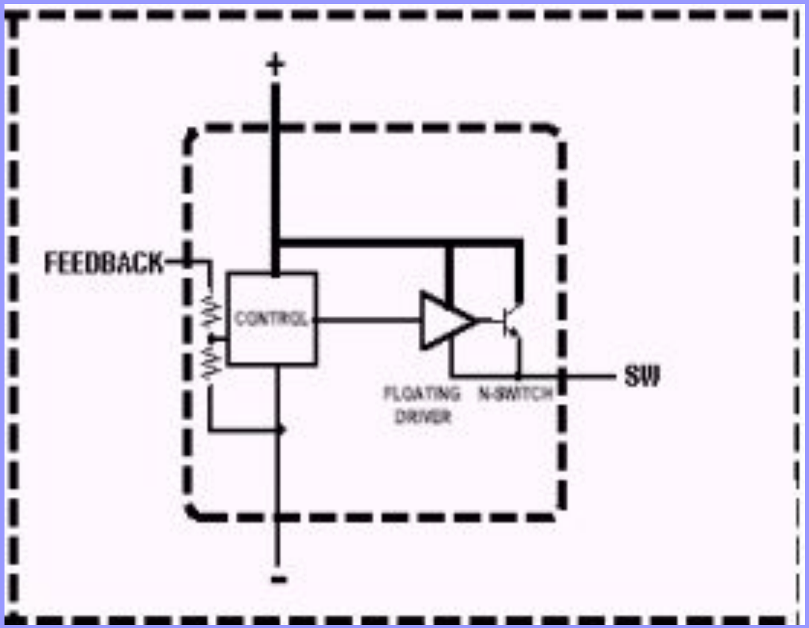
Type 2 IC ("Buck IC")



Summary of IC differences (1)

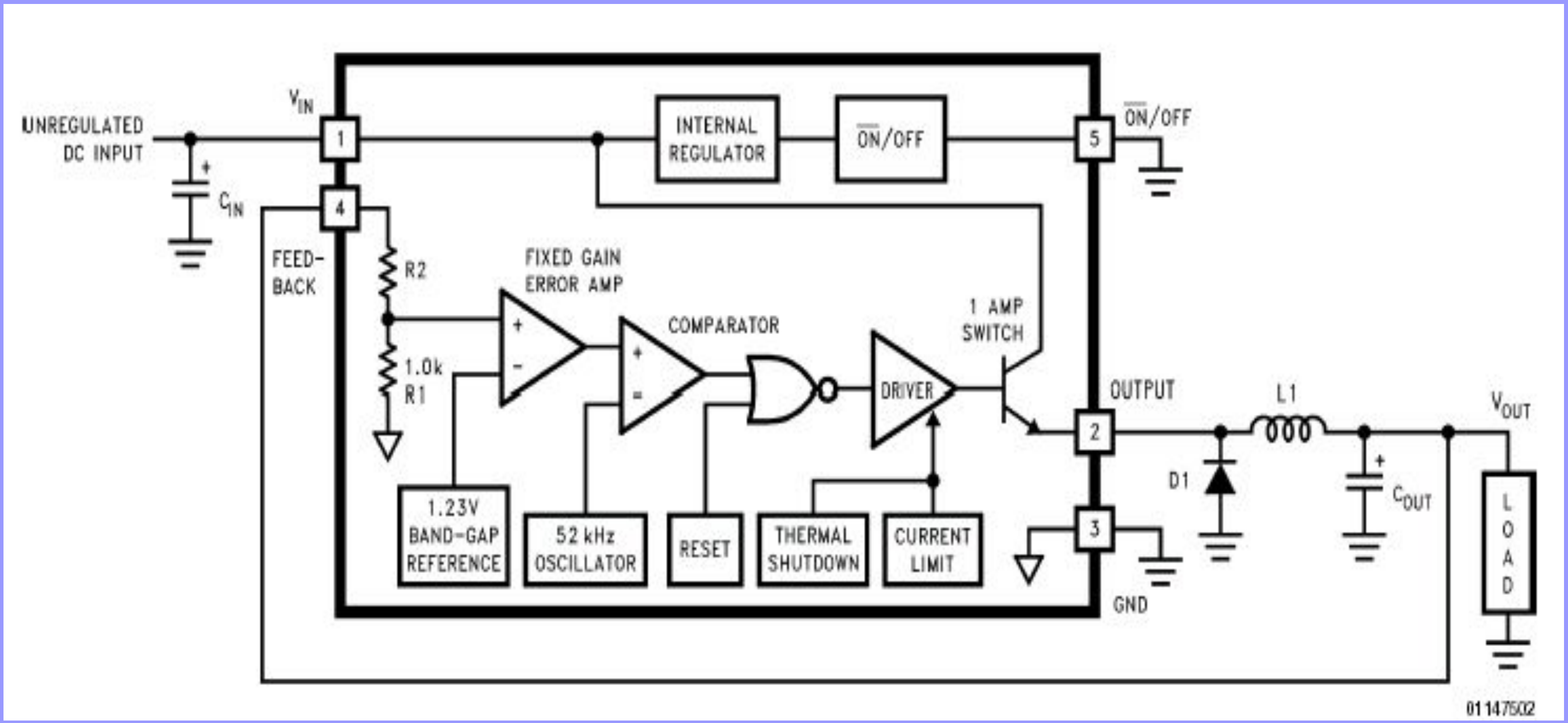
- Type 1 connects the Source/Emitter (lower voltage switch pin) to the - pin of the control block.
- Type 2 connects the Drain/Collector (higher voltage switch pin) to the + pin of the control block.

Summary of IC differences (2)



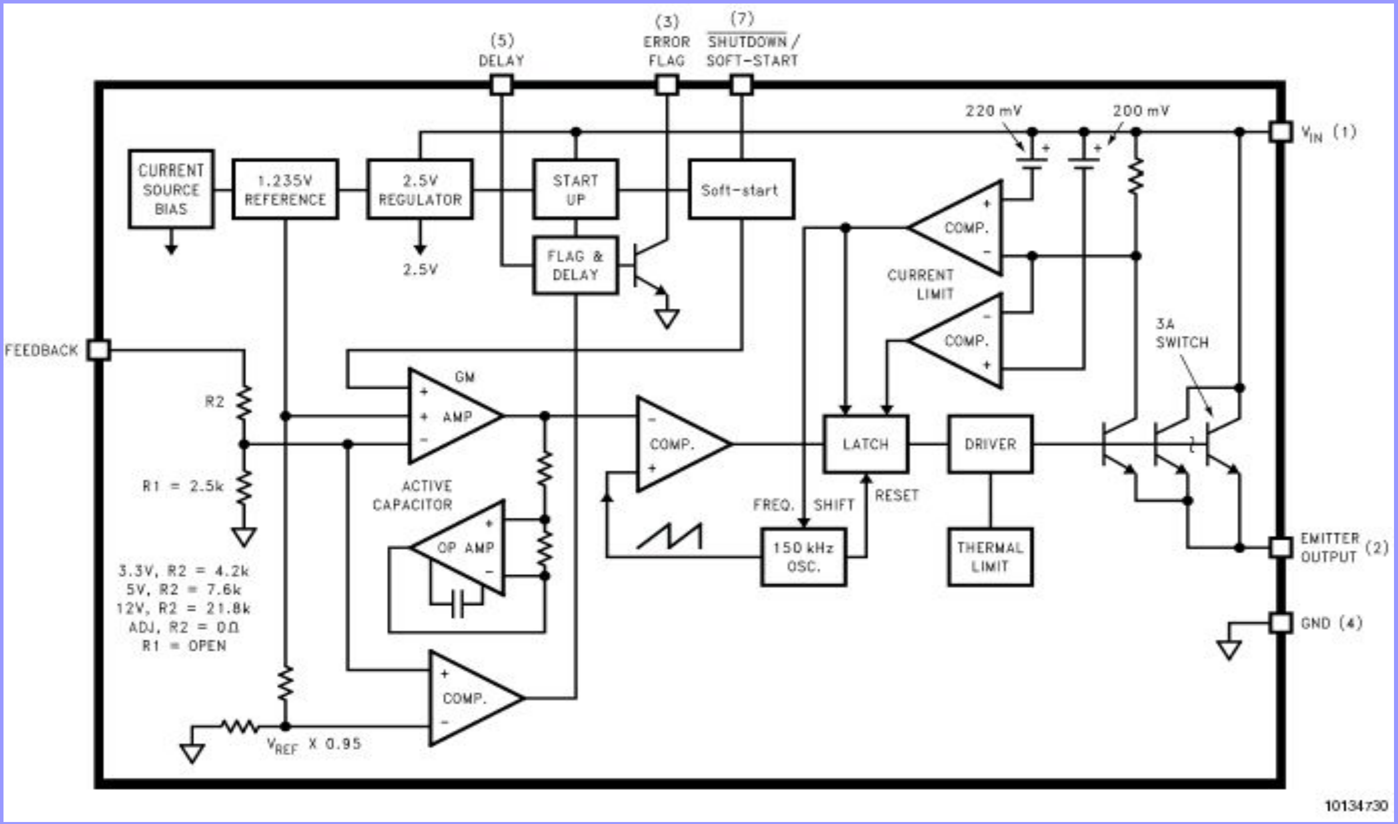
NPN switches are generally easier to drive since the Base has to be taken only slightly higher than the Emitter to turn the switch ON (note that even the small existing CE drop can be used for this purpose, as in Darlington/β-multiplier drive arrangements).

LM1575/2575



This is a Type 2 IC by our definition. Note that the NPN can be driven ‘within the input rails’.

LM2590HV

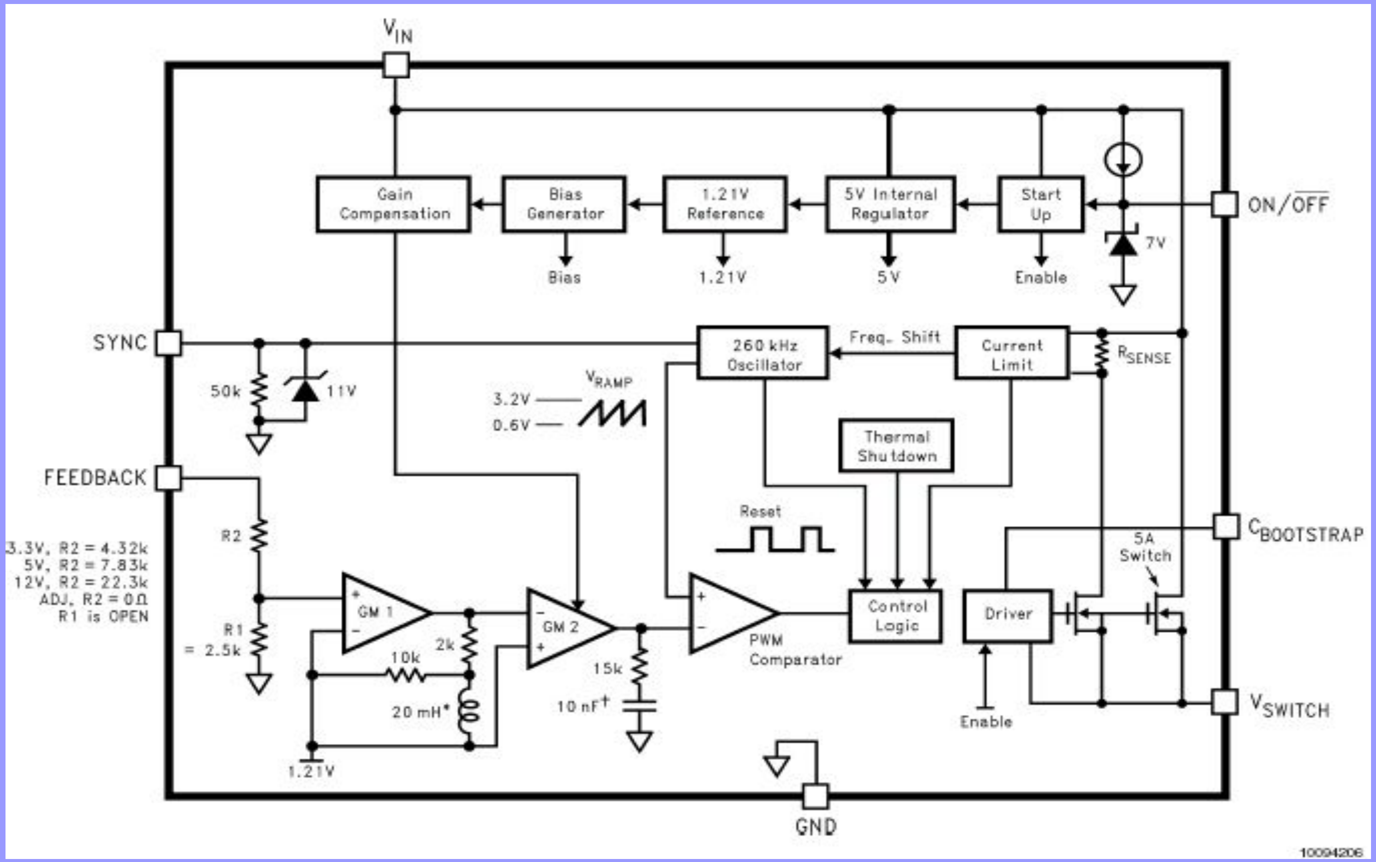


This is a Type 2 IC by our definition. Note that the NPN can be driven 'within the input rails'.

Type 2 IC's with NPN Switches

- We see that the 'drop' across the switch is uniformly high, almost irrespective of load current rating. It is always about 1.4V (worst case over temperature). You need this drop to be able to drive the Switch ON (and keep it ON). The only way to reduce this drop is to go to Type 2 IC's which use an N-Fet.

LM2670

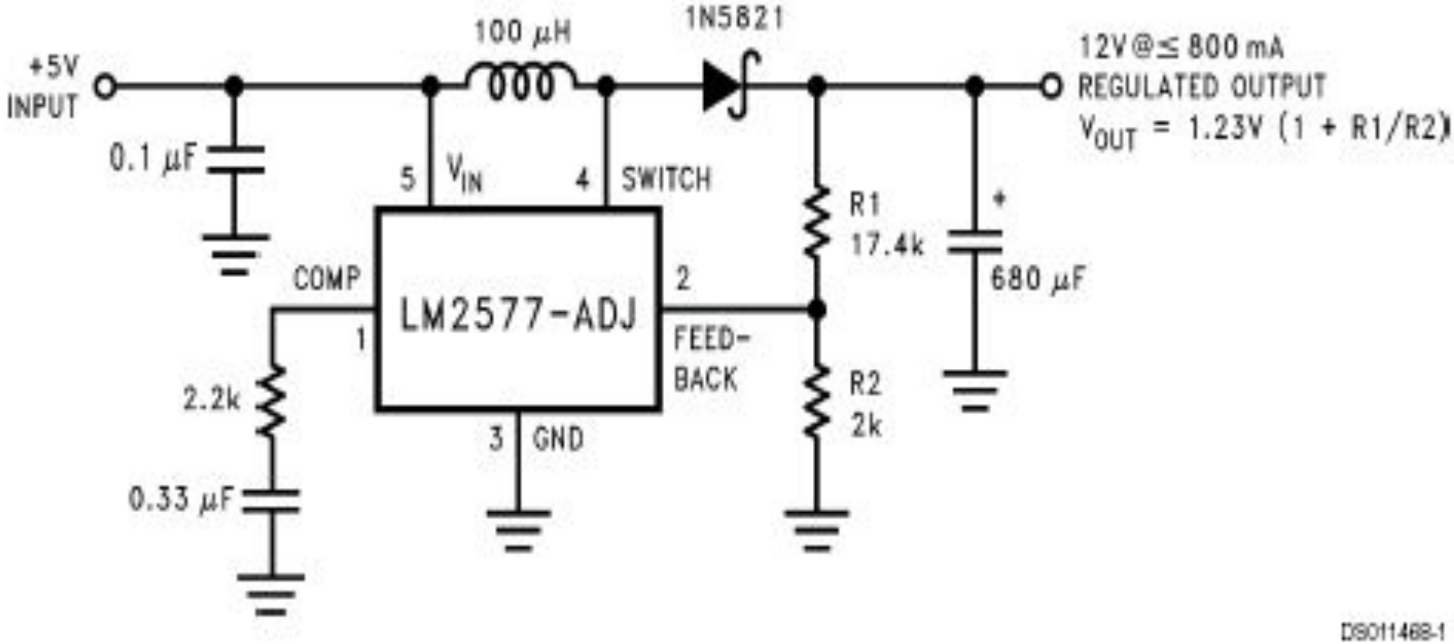


This is a Type 2 IC by our definition. Note that the N-Fet has to be driven ‘outside the input rails’.

Summary of IC differences (3)

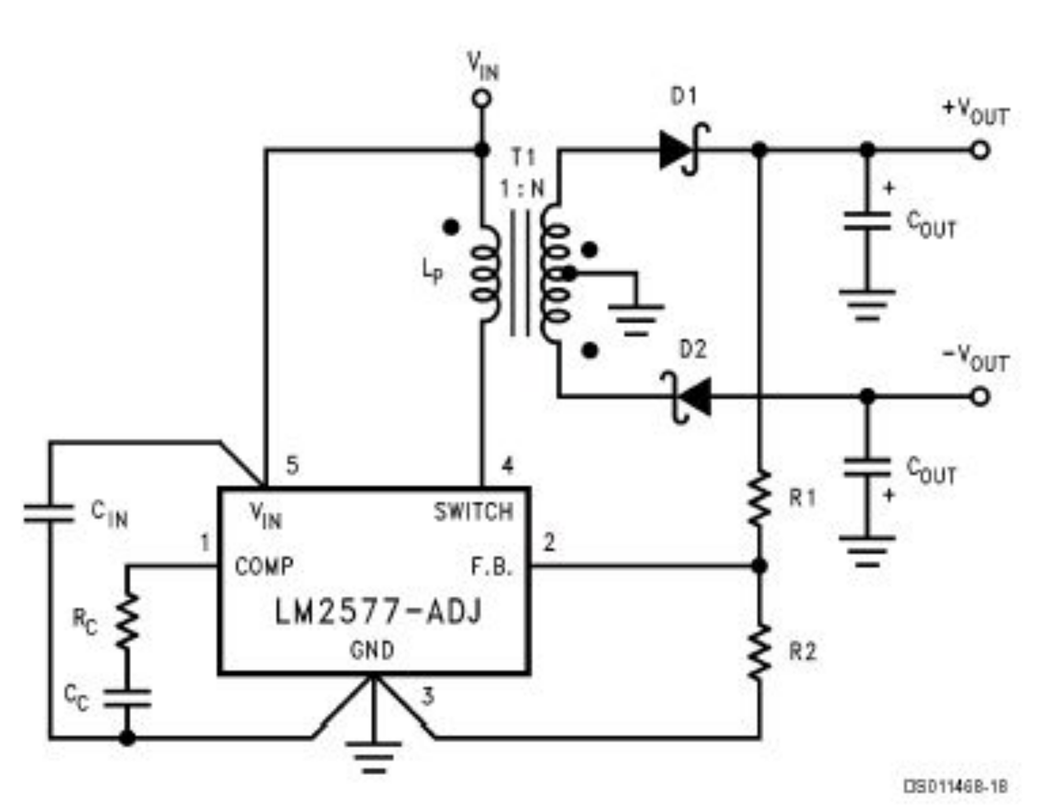
- Returning to N-switches, we can conclude that despite their advantages, the drive of FET-based Type 2 ICs are the the most complex. We must recognize that when the switch turns ON, the Source/Emitter pin becomes (almost) equal to the '+' supply pin. But to keep the FET ON, a voltage higher than the IC supply pin is required (typically 5-10 Volts higher depending on type of FET). This is not readily available as it is outside the range of the input supply rails. In fact there is no other easy way other than to *bootstrap* the driver stage, such that the driver floats on the switching node.

A 'Boost IC': the LM2577



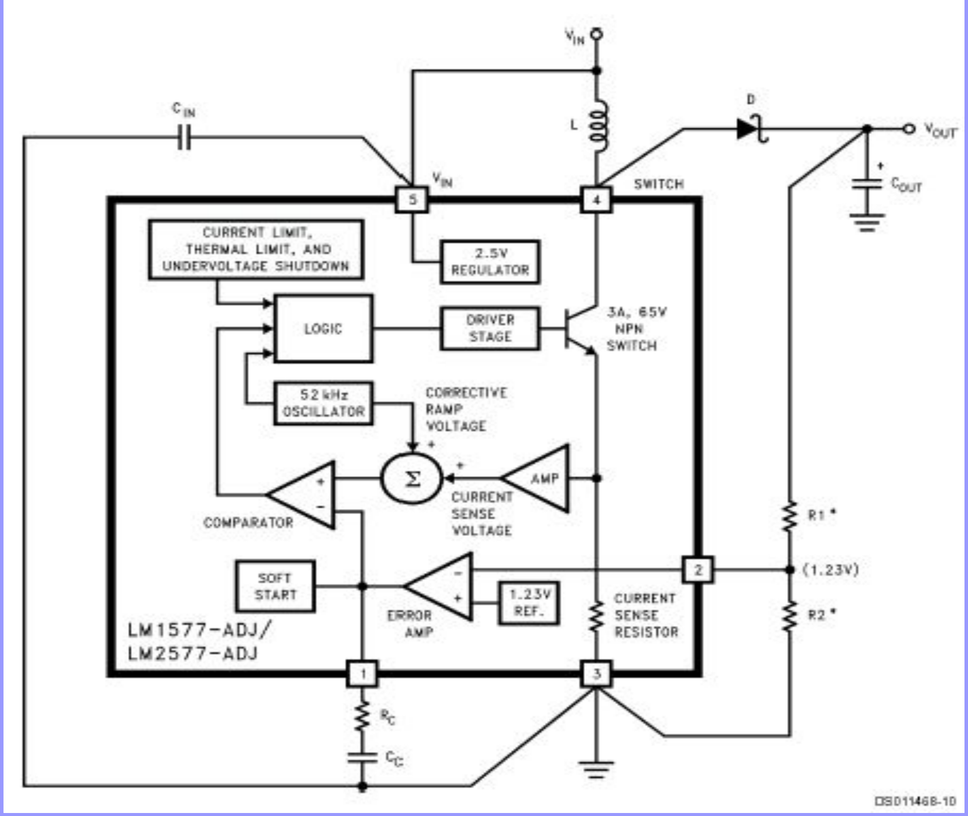
- This is a Boost application. So can IC this do Buck-Boost/Flyback????

LM2577 as a Flyback



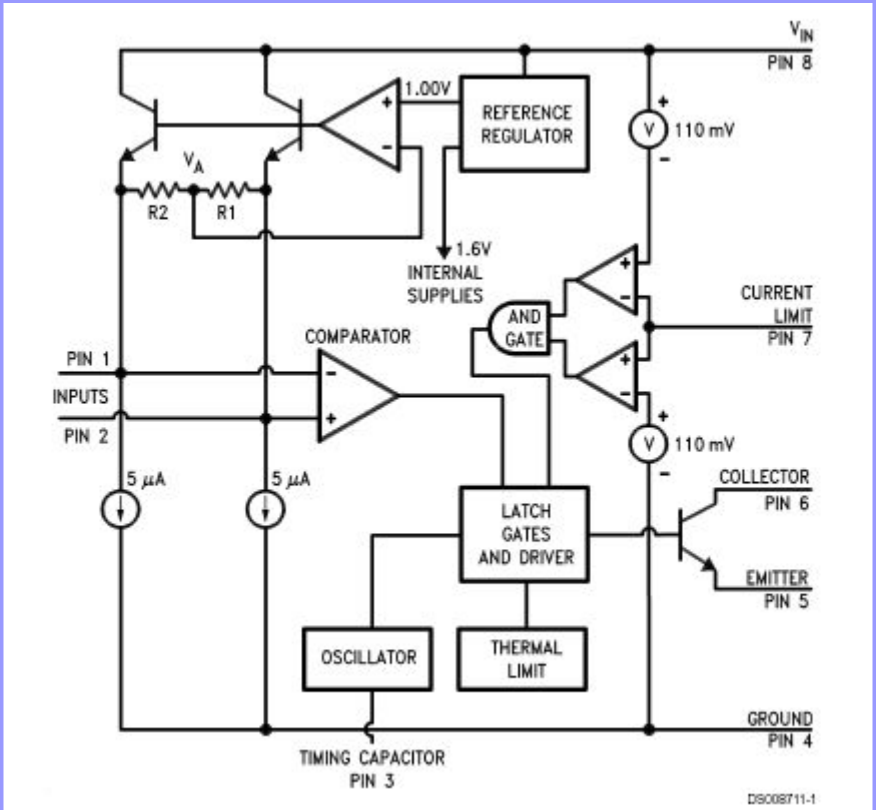
- So why wasn't this obvious right away???

LM2577: The Block Diagram



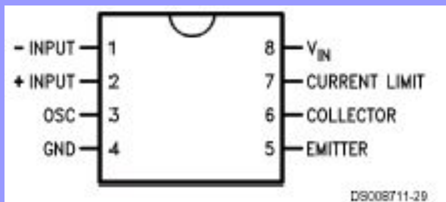
- Not very obvious, but this is a Type 1 IC!

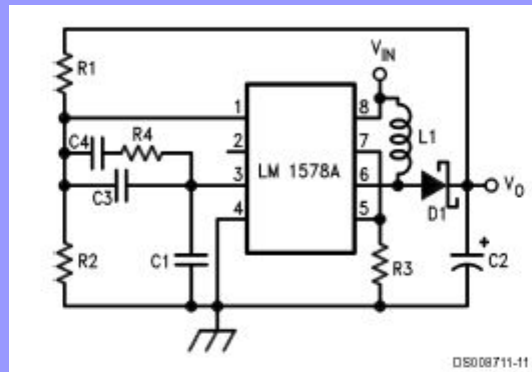
LM1578/2578/3578



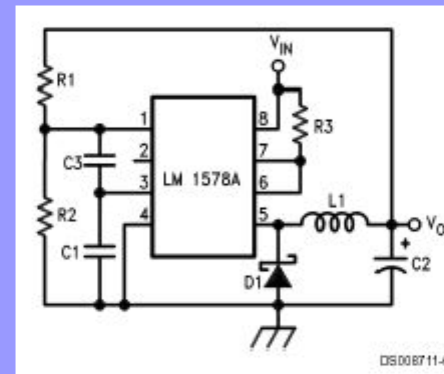
- The transistor is completely uncommitted

LM1578 Applications





V_{in} = 5V	R4 = 200 kΩ
V_O = 15V	C1 = 1820 pF
V_{ripple} = 10 mV	C2 = 470 µF
I_O = 140 mA	C3 = 20 pF
f_{osc} = 50 kHz	C4 = 0.0022 µF
R1 = 140 kΩ	L1 = 330 µH
R2 = 10 kΩ	D1 = 1N5818
R3 = 0.15Ω	



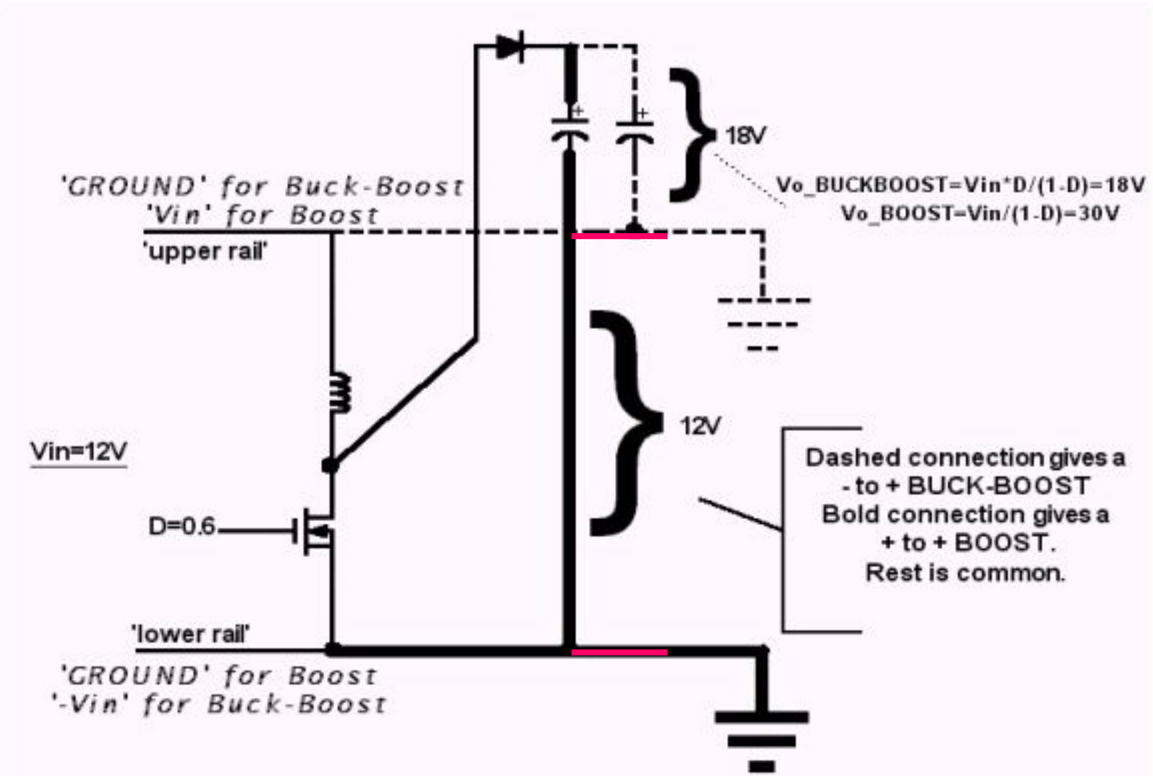
- From L to R: Pinout, +ve to +ve Boost, +ve to +ve Buck

Labeling of Pins

- Don’t be confused by the pin labels. There is unfortunately no uniformity. Different engineers have used different labels. For example….

- In a Buck (Type 1), the switching node has been called “Switch” , or “Output”.
- Therefore Identify the switching node: by definition it is the node where the switch, diode and inductor are connected
- But look at the Block Diagram first!!

How is a Boost different from a Buck-Boost?



BOOST

$$D = \frac{Vo - Vin}{Vo}$$

Solving

$$Vo = \frac{Vin}{1 - D}$$

BUCK-BOOST

$$D = \frac{Vo}{Vin + Vo}$$

Solving

$$Vo = \frac{Vin \bullet D}{1 - D}$$

- Apply D=0.6 and see what happens for each case i.e. capacitor –ve terminal connected in two ways

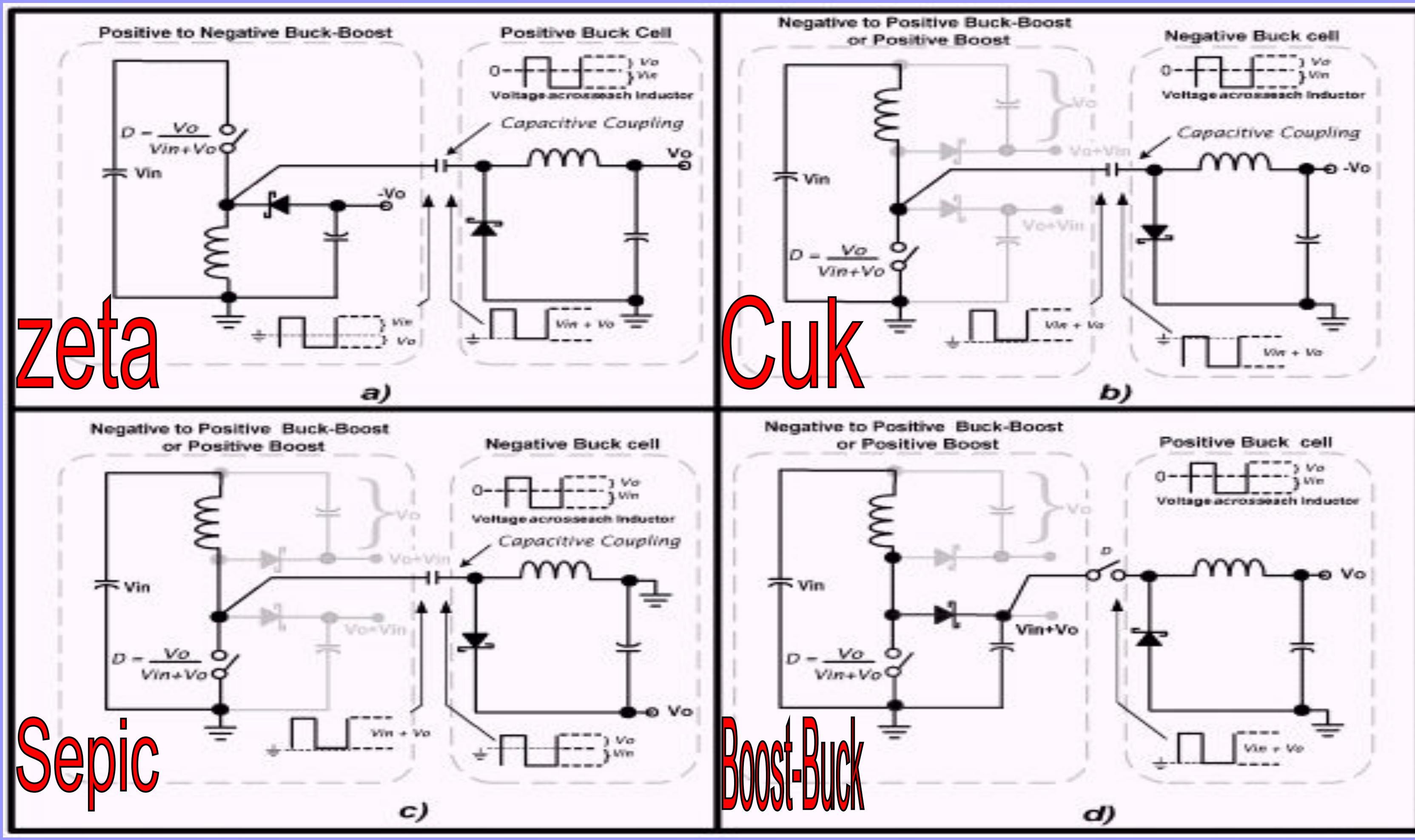
Boost and Buck-Boost compared

- The main difference is in the *feedback*. Since for a Boost, the IC control is typically always connected to the 'lower rail', a simple resistive divider across the output capacitor can be used to connect directly to the feedback pin of the IC control. But for the Buck-Boost, the output voltage is with respect to the system ground (the 'upper rail'), whereas the IC control is still referenced to the 'lower rail'. Therefore a more elaborate solution is required. This usually takes the form of a differential amplifier stage to sense the output voltage of the Buck-Boost and then to 'translate' it to the lower rail.

Nomenclature used

- In this article we will use the word ‘Flyback’ to refer exclusively to a Buck-Boost stage with inherent primary to secondary isolation. Obviously this requires a transformer. But we could also have a transformer-based Buck-Boost with no isolation present, because the primary and secondary windings are connected together for easier implementation of feedback.

Boost/Buck-Boost/what else??

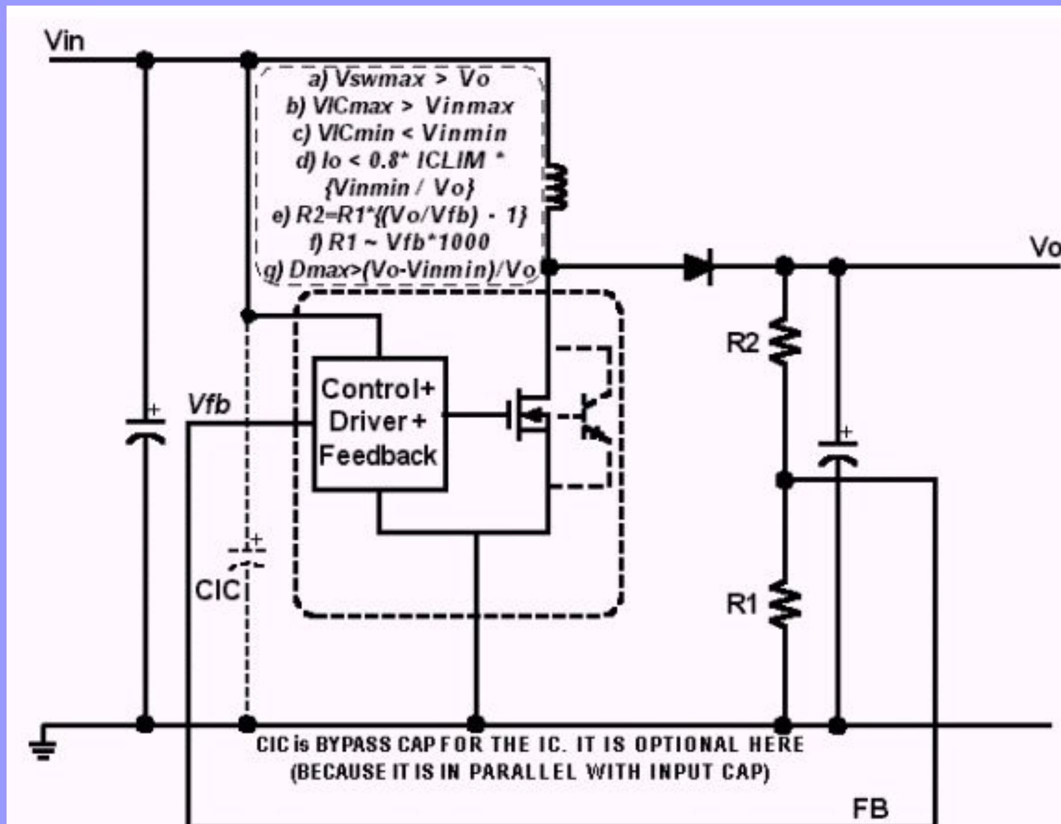


- **<u>Now the crucial chain of logic behind hidden applications:</u> the primary intended application for the Type 1 is IC is the positive to positive Boost. We know that this involves a ‘N-’ cell (Type B). Therefore we conclude that this IC is most ‘comfortable’ with any topology/configuration, provided it involves a (similar) Type B cell. This Type B cell is a ‘natural choice’ for a Type 1 IC.**

Natural Choices of a Type 1 IC

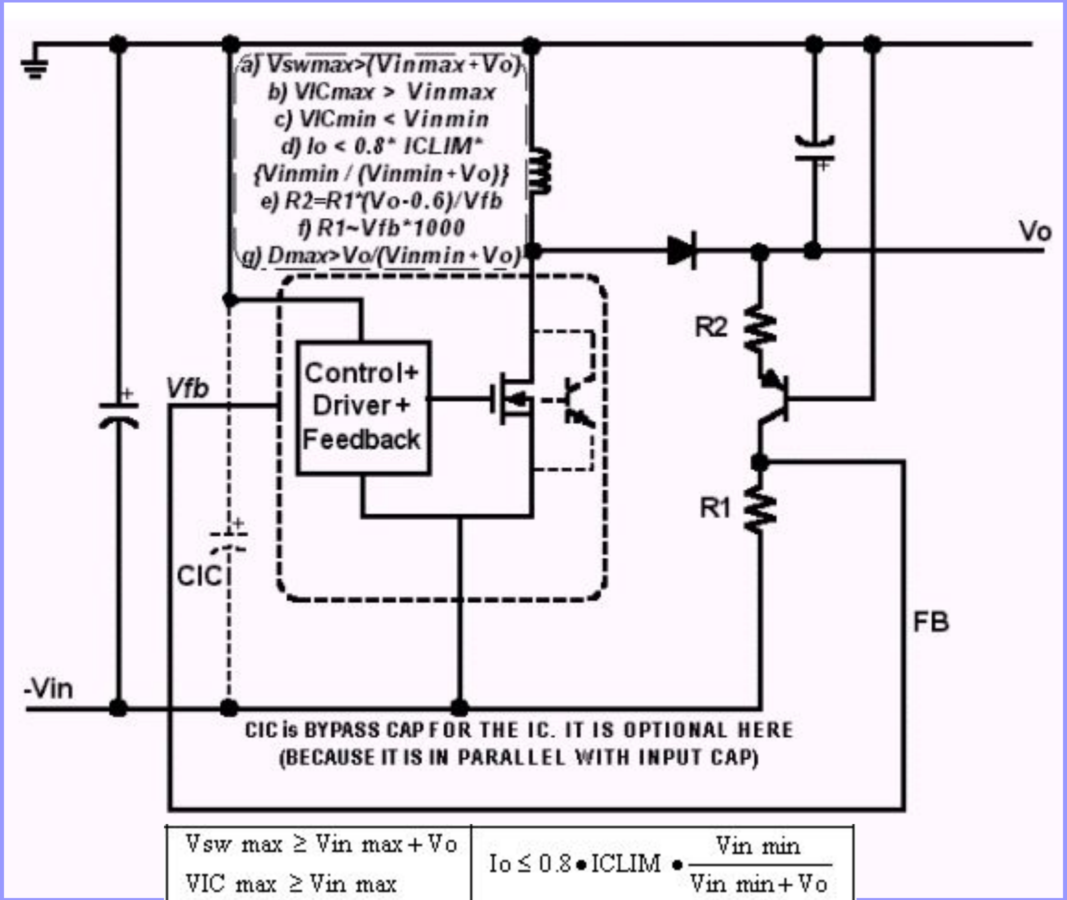
- a) Positive to Positive Boost: Uses a Type B cell. The **primary intended Application** for a Type 1 IC.
- b) Negative to Positive Buck-Boost: Uses a Type B cell. Another intended Application for a Type 1 IC.
- c) Negative to Negative Buck: Uses a Type B cell. A ‘hidden application’.

(Type B LSD Cell, Type 1 IC) +ve to +ve Boost



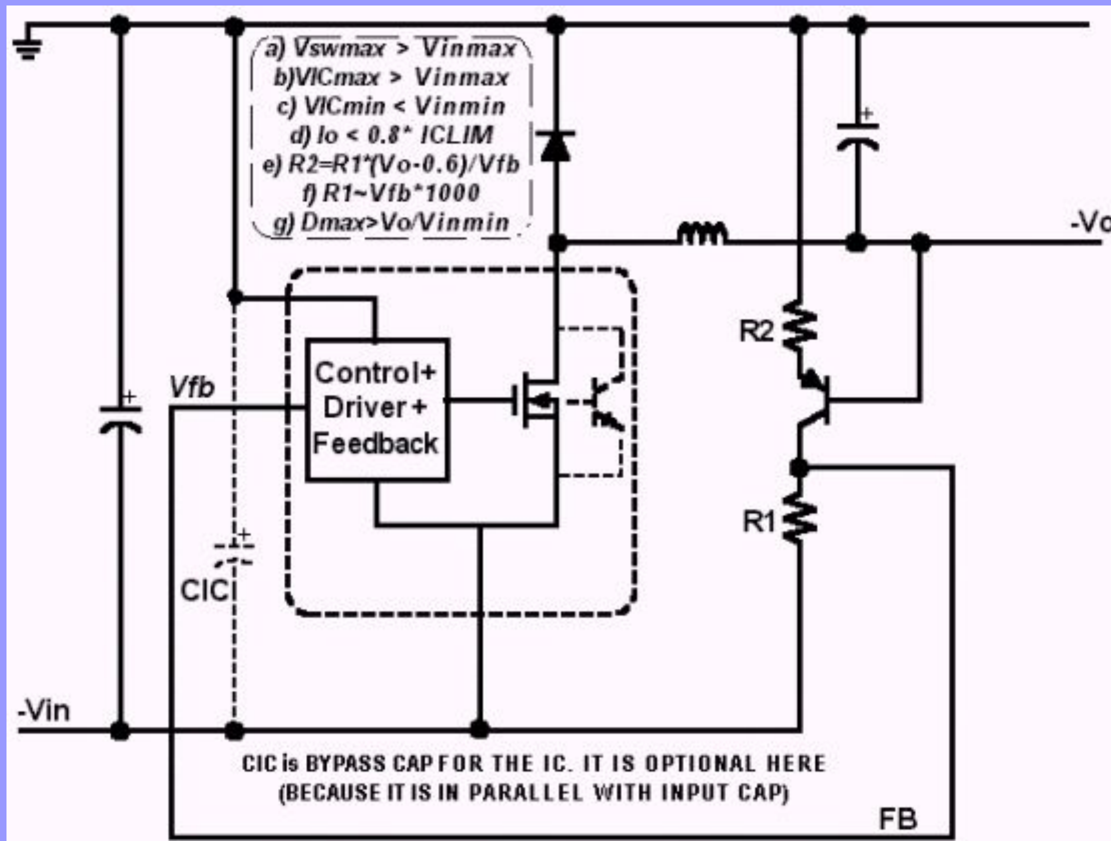
$V_{sw\,max} \ge V_o$ $V_{IC\,max} \ge V_{in\,max}$ $V_{IC\,min} \le V_{in\,min}$	$I_o \le 0.8 \bullet I_{CLIM} \bullet \frac{V_{in\,min}}{V_o}$ $R2 = R1 \bullet \left[\frac{V_o}{V_{fb}} - 1\right]$ $D_{max} \ge \frac{V_o - V_{in\,min}}{V_o}$

(Type B LSD Cell, Type 1 IC) -ve to +ve Buck-Boost



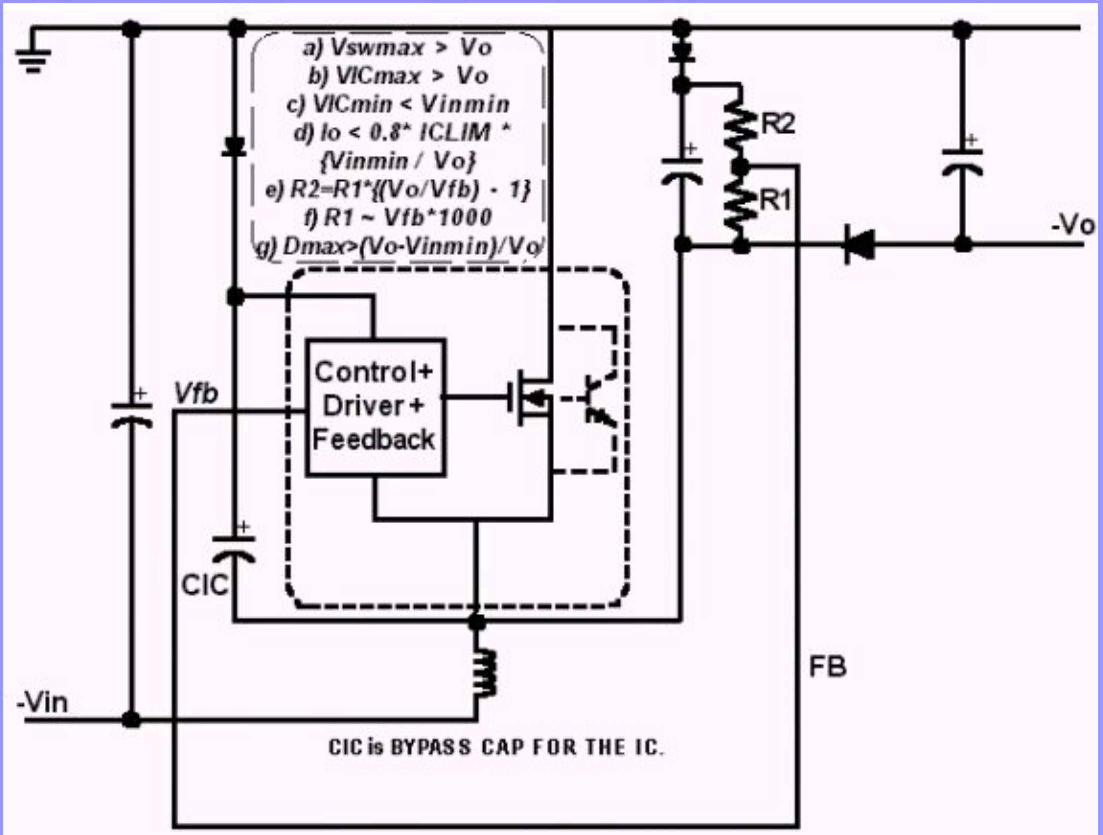
$Vsw\ max \geq Vin\ max + Vo$ $VIC\ max \geq Vin\ max$ $VIC\ min \leq Vin\ min$	$Io \leq 0.8 \bullet ICLIM \bullet \frac{Vin\ min}{Vin\ min + Vo}$ $R2 \approx R1 \bullet \left[\frac{Vo - 0.6}{Vfb} - 1\right]$ $D\ max \geq \frac{Vo}{Vin\ min + Vo}$

(Type B LSD Cell, Type 1 IC) -ve to -ve Buck



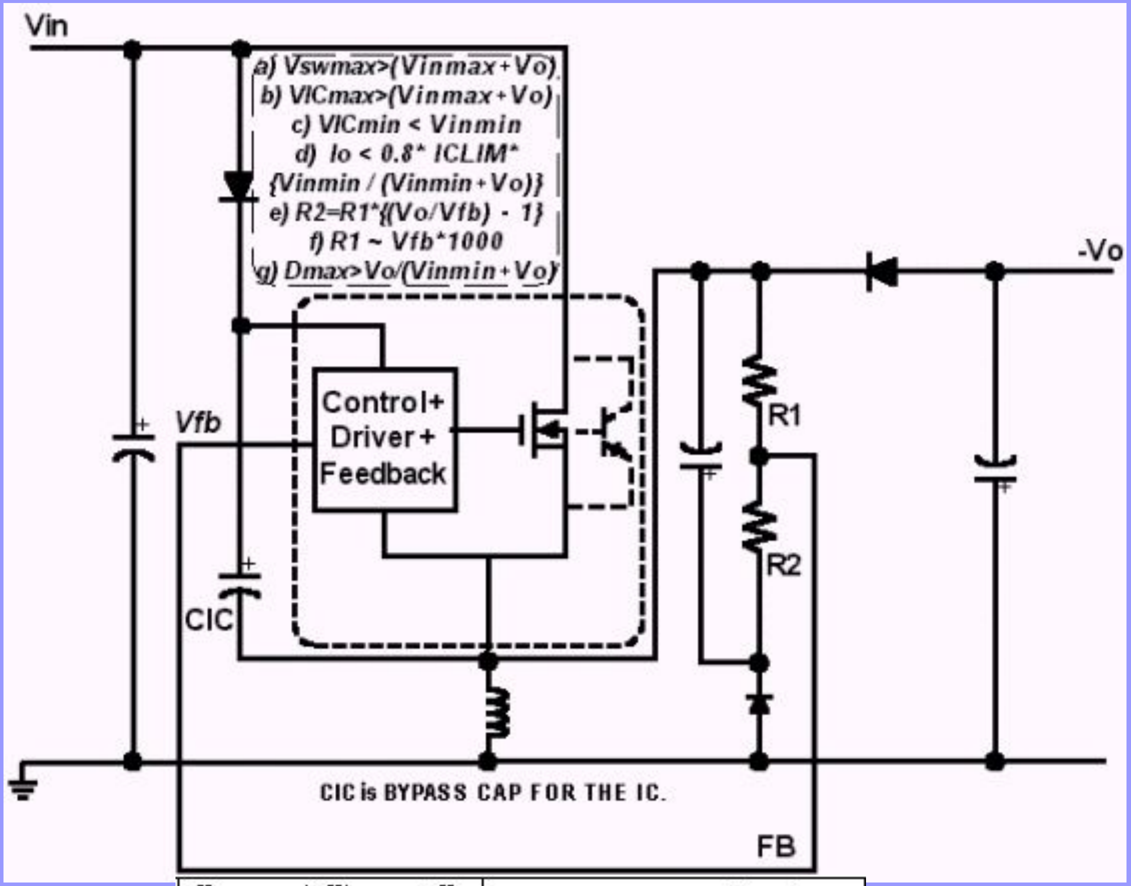
$V_{sw}\ max \geq V_{in}\ max$	$I_o \leq 0.8 \bullet ICLIM$
$VIC\ max \geq V_{in}\ max$	$R2 \approx R1 \bullet \left[\frac{V_o - 0.6}{V_{fb}} - 1\right]$
$VIC\ min \leq V_{in}\ min$	$D\ max \geq \frac{V_o}{V_{in}\ min}$

(Type A LSD Cell, Type 1 IC)
-ve to -ve Boost



$Vsw\ max \geq Vo$ $VIC\ max \geq Vo$ $VIC\ min \leq Vin\ min$	$Io \leq 0.8 \bullet ICLIM \bullet \frac{Vin\ min}{Vo}$ $R2 \approx R1 \bullet \left[\frac{Vo}{Vfb} - 1\right]$ $D\ max \geq \frac{Vo - Vin\ min}{Vo}$

(Type A LSD Cell, Type 1 IC) +ve to -ve Buck-Boost



$Vsw\ max \geq Vin\ max + Vo$ $VIC\ max \geq Vin\ max + Vo$ $VIC\ min \leq Vin\ min$	$Io \leq 0.8 \bullet ICLIM \bullet \frac{Vin\ min}{Vin\ min + Vo}$ $R2 = R1 \bullet \left[\frac{Vo}{Vfb} - 1\right]$ $D\ max \geq \frac{Vo}{Vin\ min + Vo}$

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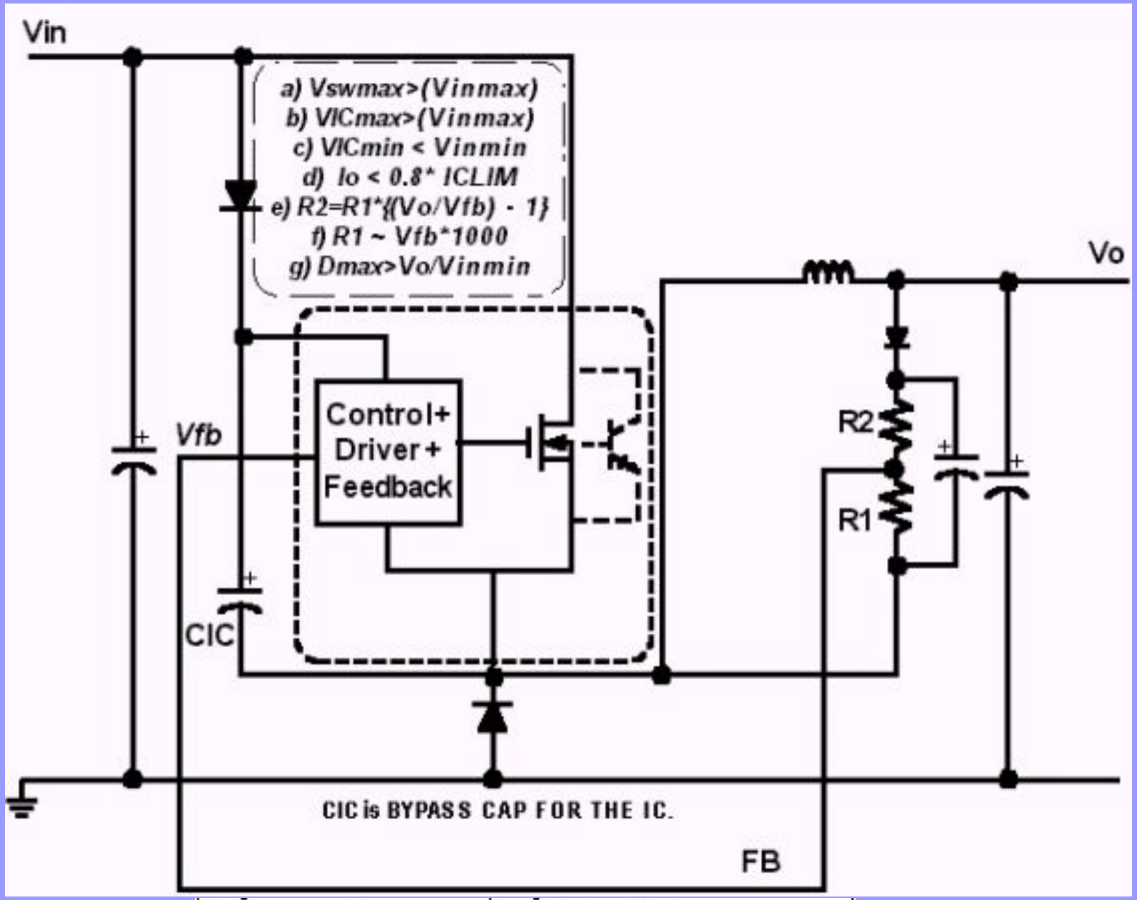
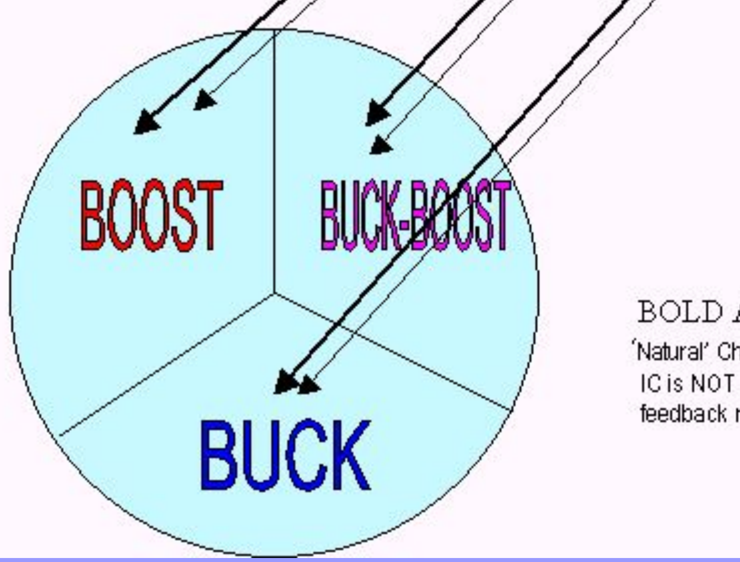
(Type A LSD Cell, Type 1 IC) +ve to +ve Buck



$V_{sw\,max} \geq V_{in\,max}$	$I_o \leq 0.8 \bullet I_{CLIM}$
$V_{IC\,max} \geq V_{in\,max}$	$R2 \approx R1 \bullet \left[\frac{V_o}{V_{fb}} - 1\right]$
$V_{IC\,min} \leq V_{in\,min}$	$D_{max} \geq \frac{V_o}{V_{in\,min}}$

Summary of Type 1 IC Applications

BOOST	Positive to Positive	(N-switch)	Type B
	Negative to Negative	(N-switch)	Type A
	Positive to Positive	(P-switch)	Type C
	Negative to Negative	(P-switch)	Type D
BUCK-BOOST	Negative to Positive	(N-switch)	Type B
	Positive to Negative	(N-switch)	Type A
	Negative to Positive	(P-switch)	Type C
	Positive to Negative	(P-switch)	Type D
BUCK	Negative to Negative	(N-switch)	Type B
	Positive to Positive	(N-switch)	Type A
	Negative to Negative	(P-switch)	Type C
	Positive to Positive	(P-switch)	Type D

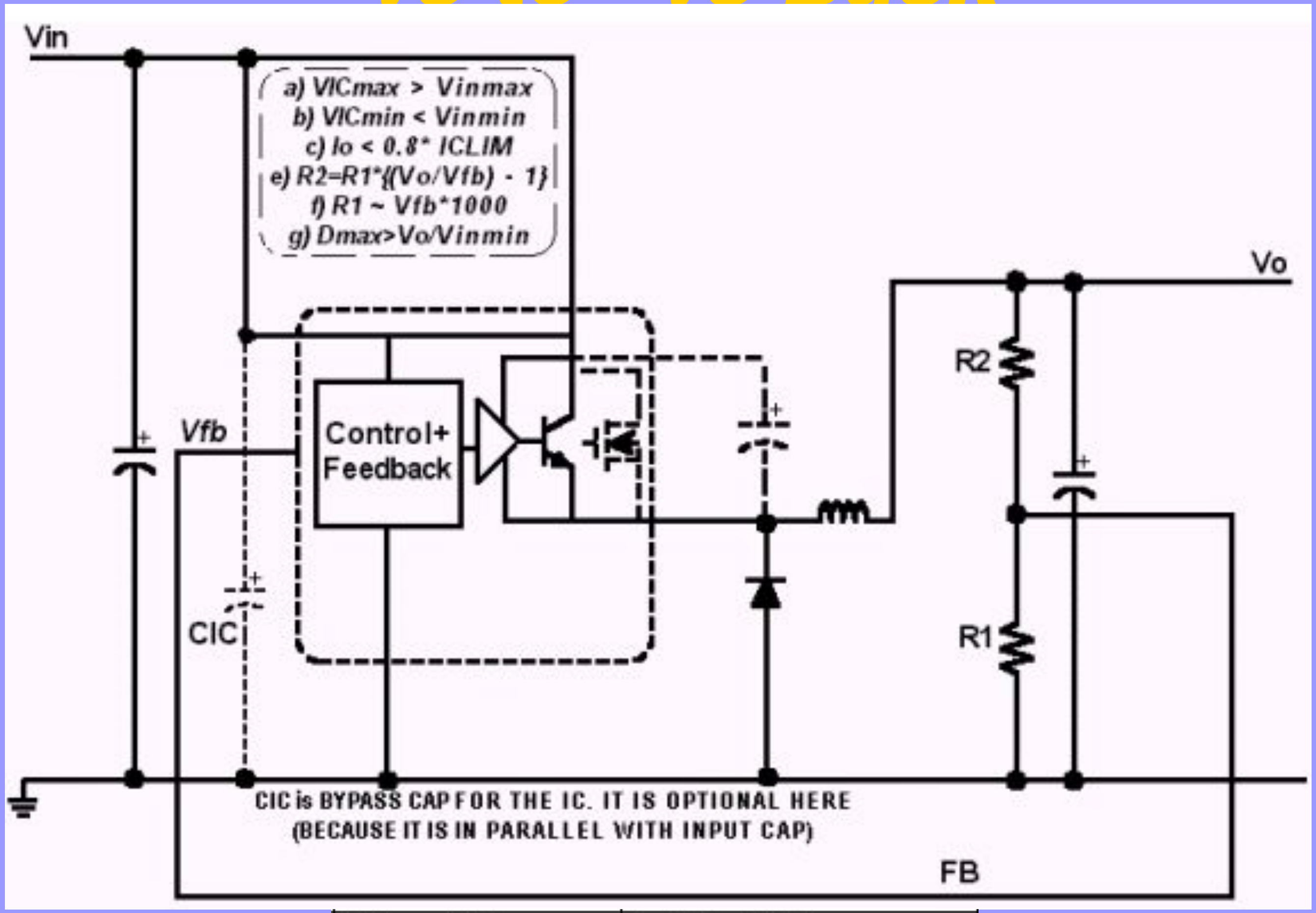


BOLD ARROWS:
'Natural' Choice (Ground of IC is NOT swinging, feedback method direct)

Natural Choices of a Type 2 IC

- a) Positive to Positive Buck: Uses a Type A cell. The **primary intended Application** for a Type 2 IC.
- b) Positive to Negative Buck-Boost: Uses a Type A cell. Additional IC bypass capacitor required.
- c) Negative to Negative Boost: Uses a Type A cell. Additional IC bypass capacitor required.

(Type A LSD Cell, Type 2 IC) +ve to +ve Buck



$VIC\ max \geq Vin\ max$ $VIC\ min \leq Vin\ min$	$Io \leq 0.8 \bullet ICLIM$ $R2 = R1 \bullet \left[\frac{Vo}{Vfb} - 1\right]$ $D\ max \geq \frac{Vo}{Vin\ min}$

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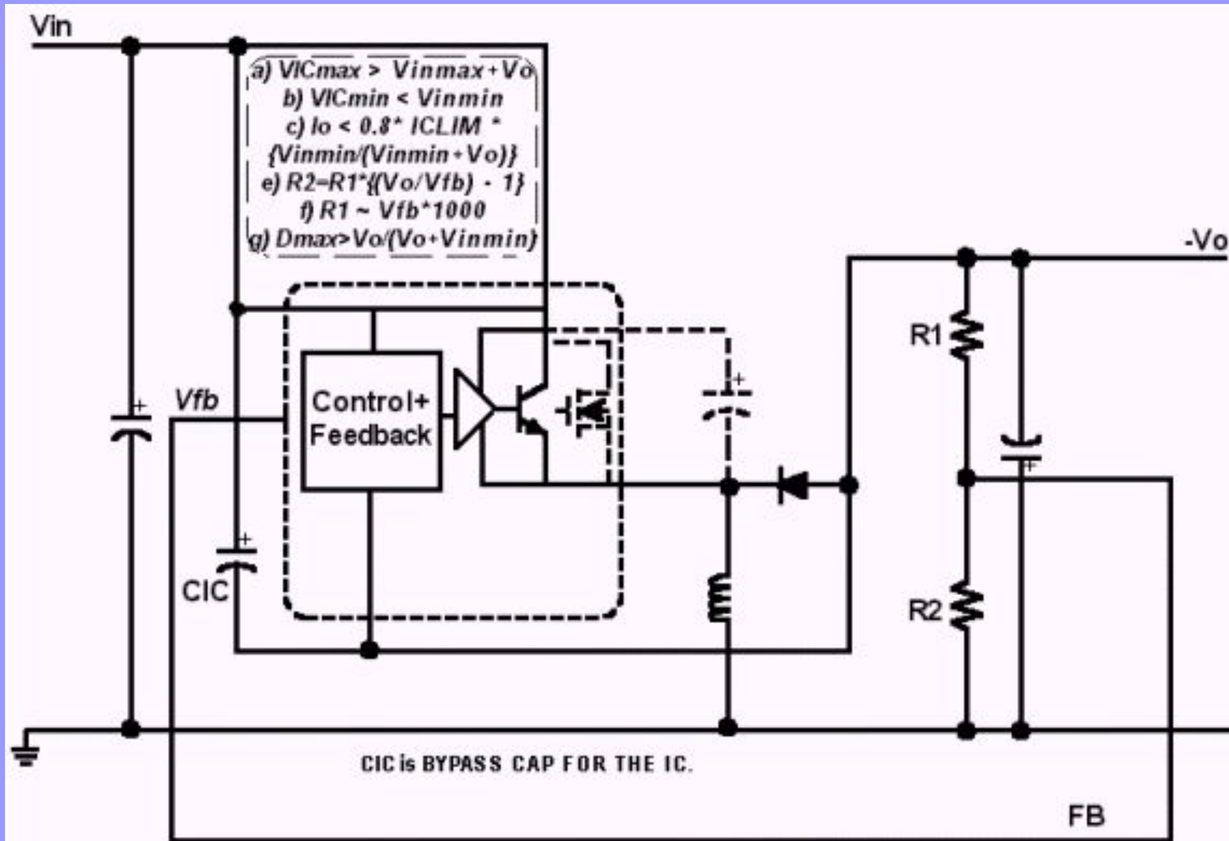
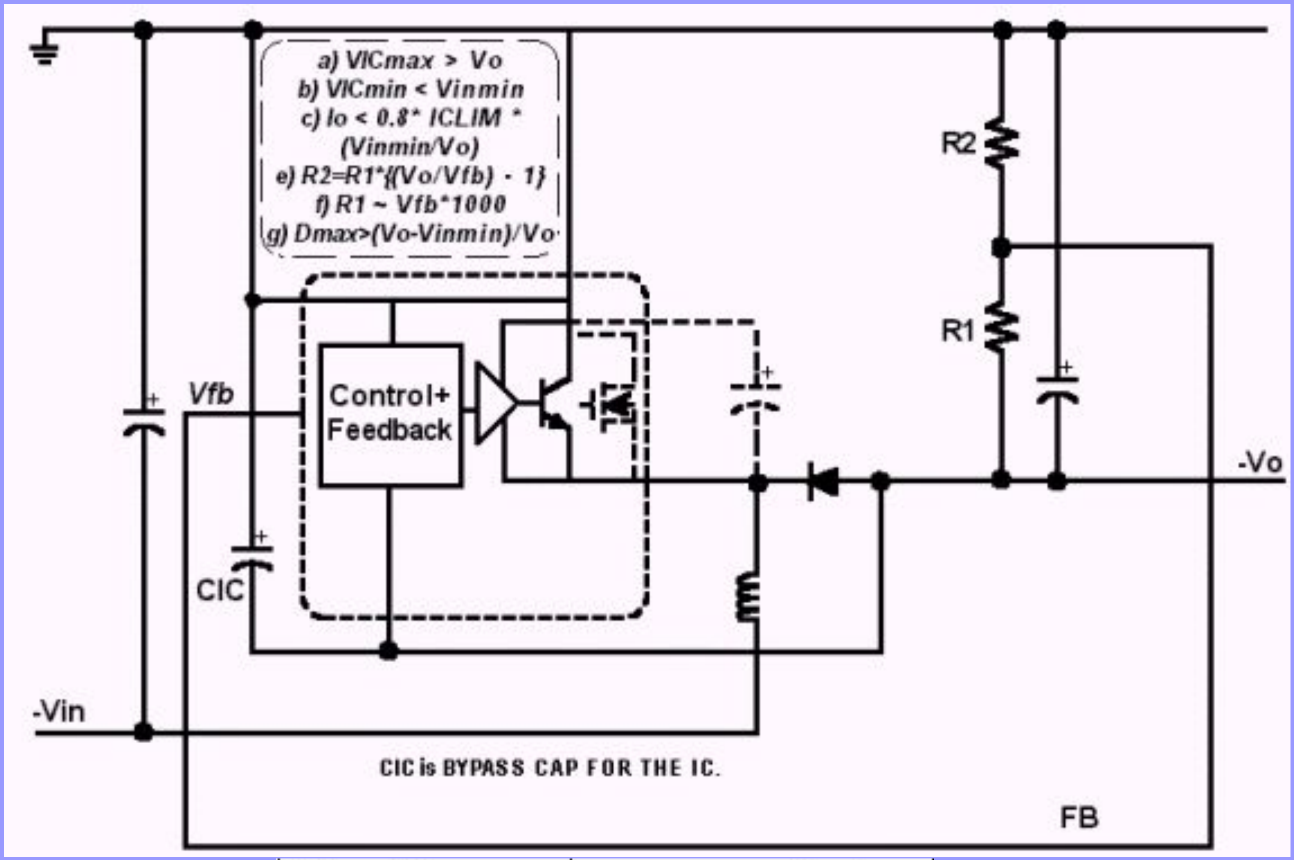
(Type A LSD Cell, Type 2 IC) +ve to -ve Buck-Boost



$VIC\ max \geq Vin\ max + Vo$ $VIC\ min \leq Vin\ min$	$Io \leq 0.8 \bullet ICLIM \bullet \frac{Vin\ min}{Vin\ min + Vo}$ $R2 = R1 \bullet \left[\frac{Vo}{Vfb} - 1\right]$ $D\ max \geq \frac{Vo}{Vin\ min + Vo}$

(Type A LSD Cell, Type 2 IC) -ve to -ve Boost



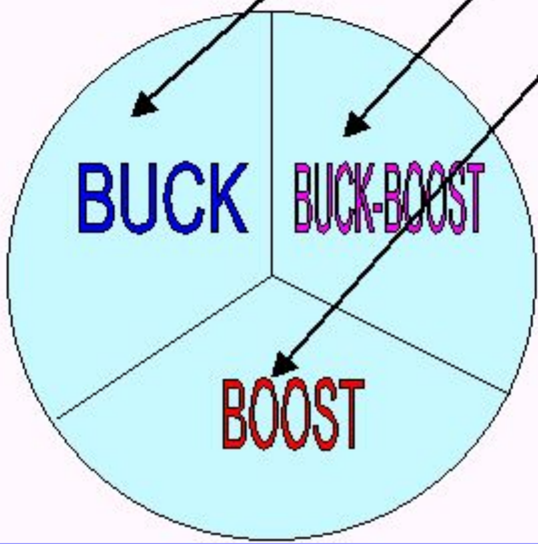
$VIC\ max \geq Vo$ $VIC\ min \leq Vin\ min$	$Io \leq 0.8 \bullet ICLIM \bullet \frac{Vin\ min}{Vo}$ $R2 = R1 \bullet \left[\frac{Vo}{Vfb} - 1\right]$ $D\ max \geq \frac{Vo - Vin\ min}{Vo}$

‘Forced’ Choices for Type 2 IC?

- Because the Drain/Collector is NOT uncommitted, it is not possible to have a Type 1 IC to perform in any application involving a cell that was not its intended cell. Therefore ‘forced’ choices are not possible.

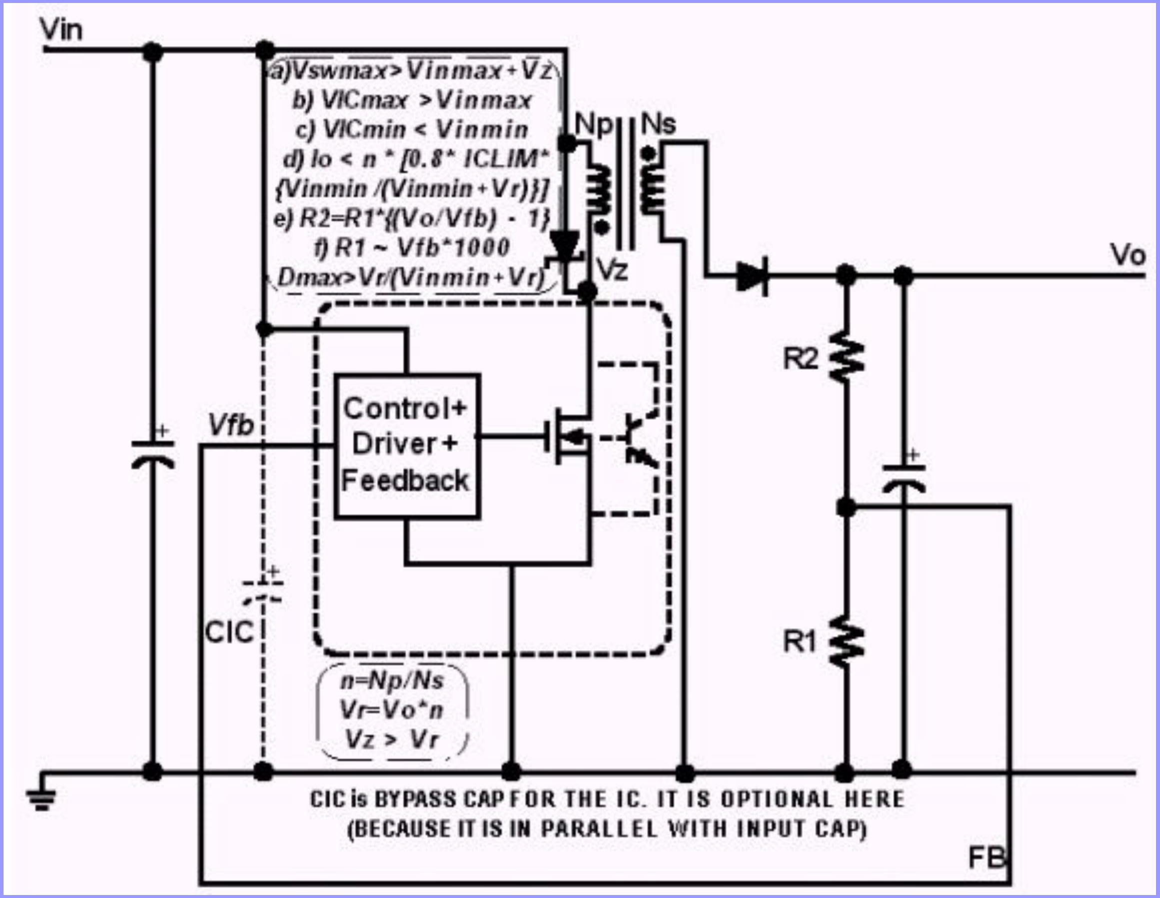
Summary of Type 2 IC Applications

BUCK	Positive to Positive	(N-switch)	Type A
	Negative to Negative	(N-switch)	Type B
	Positive to Positive	(P-switch)	Type D
	Negative to Negative	(P-switch)	Type C
BUCK-BOOST	Positive to Negative	(N-switch)	Type A
	Negative to Positive	(N-switch)	Type B
	Positive to Negative	(P-switch)	Type D
	Positive to Negative	(P-switch)	Type C
BOOST	Negative to Negative	(N-switch)	Type A
	Positive to Positive	(N-switch)	Type B
	Negative to Negative	(P-switch)	Type D
	Positive to Positive	(P-switch)	Type C

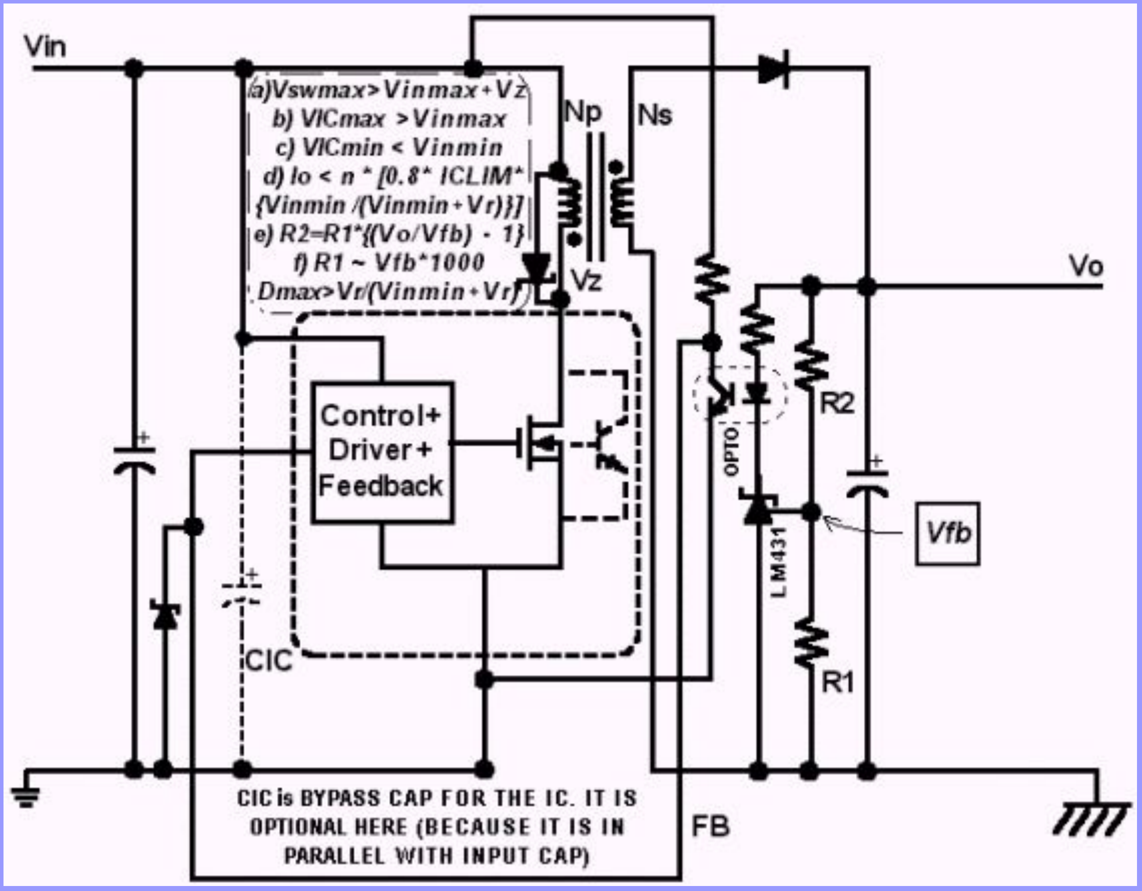


BOLD ARROWS:
'Natural' Choice (Ground of IC is NOT swinging, feedback method direct)

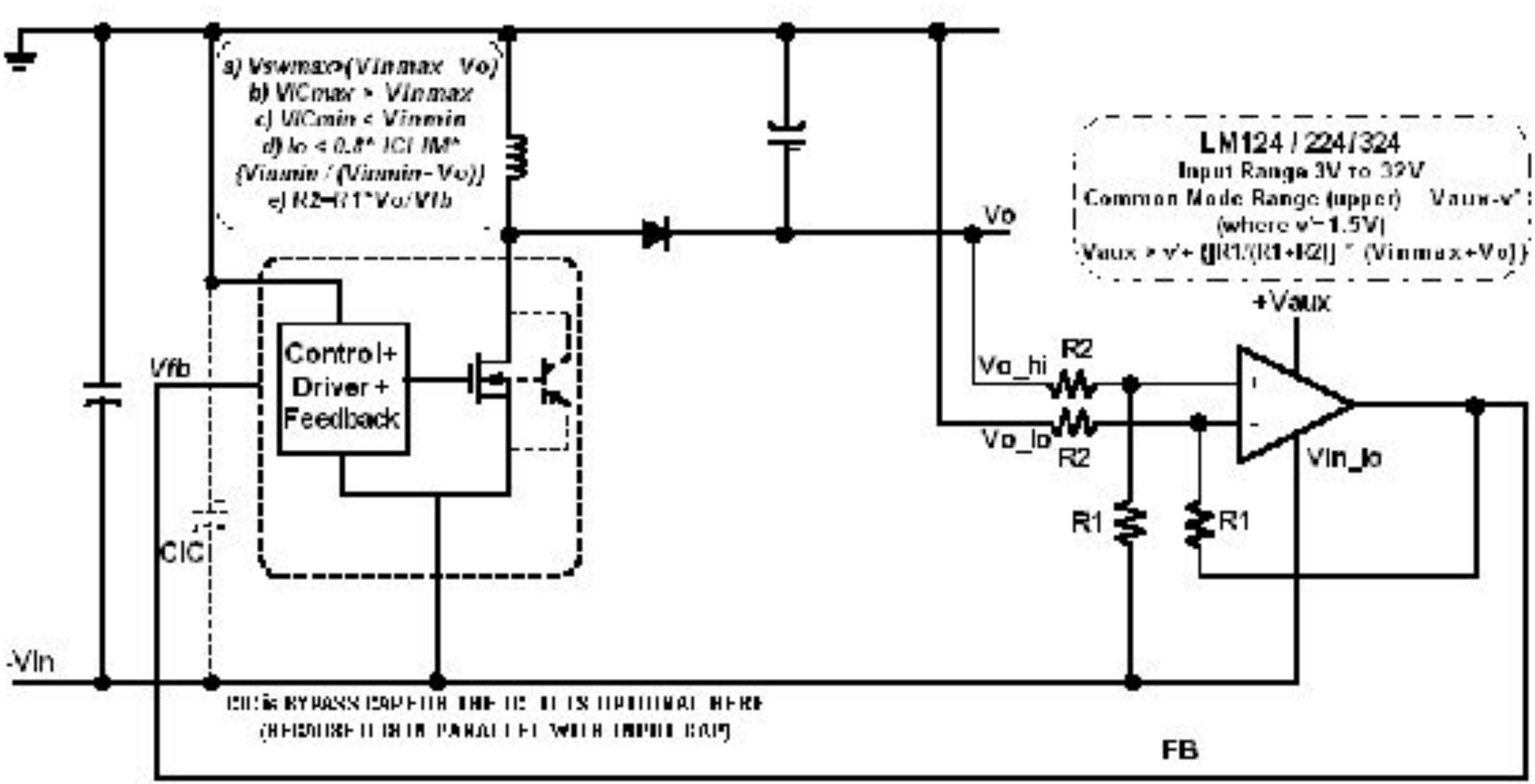
Transformer-based Type 1 Applications (1)



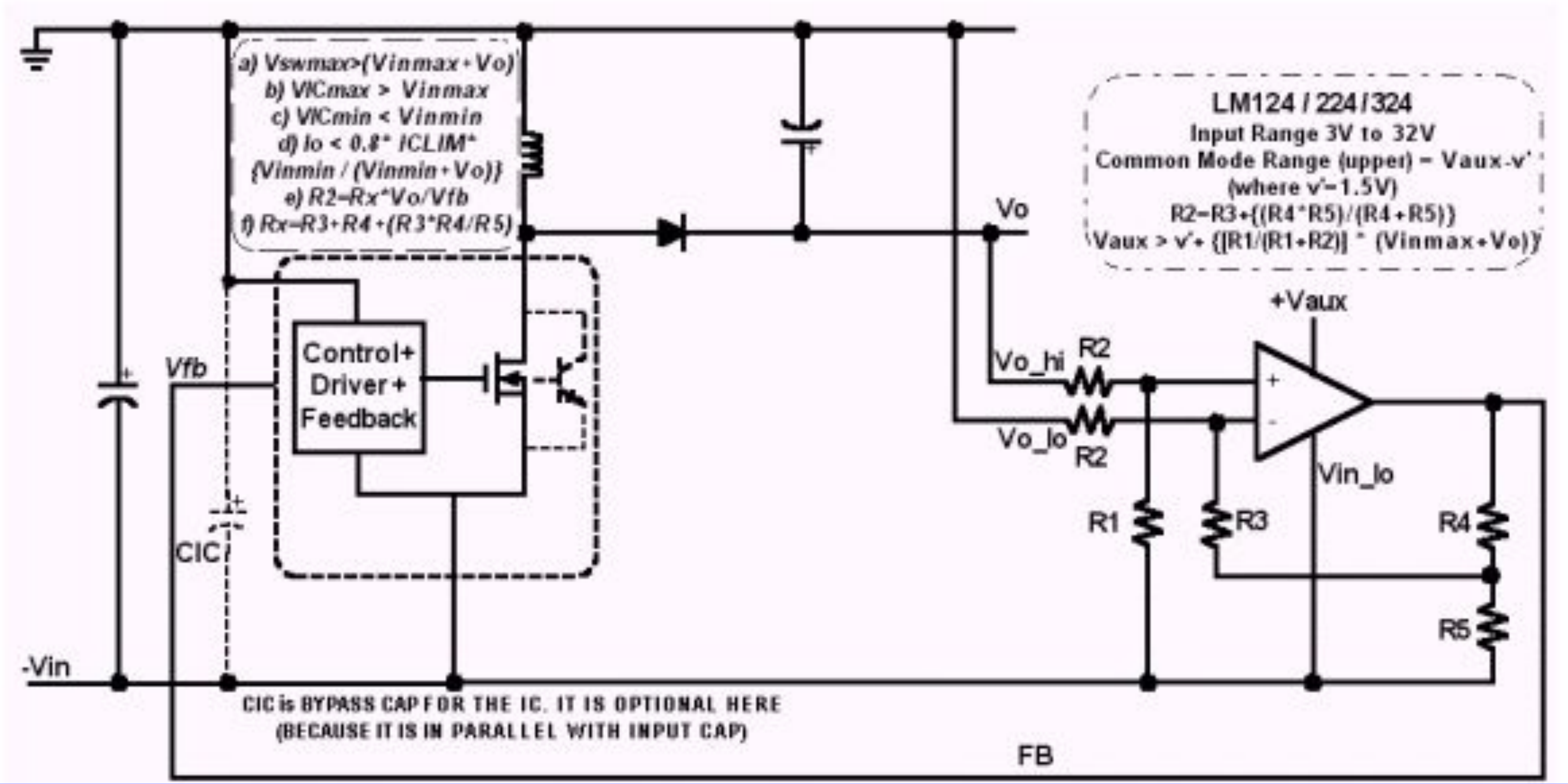
Transformer-based Type 1 Applications (2)



Differential Sensing Techniques (1)



Differential Sensing Techniques (2)



Equations for Differential Sense

Op-Amp	Equation Set
Standard Differential Amp.	$R2 = R1 \bullet Vo / Vfb$ $Vaux \geq V+\left[\frac{R1}{R1+R2} \bullet (Vin\ max + Vo)\right]$
Hi-Gain Differential Amp.	$R2 = Rx \bullet Vo / Vfb$ $Rx \equiv R3 + R4 + \frac{R3 \bullet R4}{R5}$ $R2 = R3 + \frac{R4 \bullet R5}{R4+R5}$ $Vaux \geq V+\left[\frac{R1}{R1+R2} \bullet (Vin\ max + Vo)\right]$

Summary of Applications

Type 1_N Applications: LSD cell is B

BUCK			BOOST			BUCK-BOOST		
+ve to +ve	LSD: A	POK	+ve to +ve	LSD: B	AOK			
-ve to -ve	LSD: B	OK	-ve to -ve	LSD: A	POK			
						+ve to -ve	LSD: A	POK
						-ve to +ve	LSD: B	AOK

Also include for this type of IC the following possibilities as preliminary choices (to be validated later):

Cuk: +ve to –ve

Sepic: +ve to +ve

Type 2_N Applications: LSD cell is A

BUCK			BOOST			BUCK-BOOST		
+ve to +ve	LSD: A	AOK	+ve to +ve	LSD: B	NOK			
-ve to -ve	LSD: B	NOK	-ve to -ve	LSD: A	OK			
						+ve to -ve	LSD: A	OK
						-ve to +ve	LSD: B	NOK

Type 2_P Applications: LSD cell is D

BUCK			BOOST			BUCK-BOOST		
+ve to +ve	LSD: D	AOK	+ve to +ve	LSD: C	NOK			
-ve to -ve	LSD: C	NOK	-ve to -ve	LSD: D	OK			
						+ve to -ve	LSD: D	OK
						-ve to +ve	LSD: C	NOK

Example 1

- The LM2585 is a ‘3A Flyback regulator’. Can it be used in a Boost topology? And for what range?

The MIN value of its internal current limit is 3A. Its input operating voltage range is 4V to 40V. Its switch can withstand 65V.

Example 1 (contd)

$V_{sw\,max} \geq V_o$ $VIC\ max \geq V_{in\,max}$ $VIC\ min \leq V_{in\,min}$	$I_o \leq 0.8 \bullet ICLIM \bullet \frac{V_{in\,min}}{V_o}$ $R2 = R1 \bullet \left[\frac{V_o}{V_{fb}} - 1\right]$ $D\,max \geq \frac{V_o - V_{in\,min}}{V_o}$

- This is the checklist.
- We see that the input voltage must be below 40V and the output voltage must be below 65V (since Vswmax > Vo and VICmax > Vinmax). These define the input/output voltage conditions for any suitable application. So if the output is set to 60V and the input ranges from say 20V to 40V, the maximum load (with a suitably designed practical inductor) is 0.8A:

$$I_o = 0.8 \times 3 \times \left[\frac{20}{60}\right] = 0.8A$$

Example 2

- The required application conditions are Vin ranging from 4.5V to 5.5V. The output requirement is –5V at 0.5A. Can the LM2651 be used?

LM2651 is a '1.5A Buck Regulator'. Note firstly that this IC can deliver 1.5A in a Buck configuration, but not so in any other configuration/topology. The load rating must then be re-calculated

Example 2 (contd)

$VIC\ max \geq Vin\ max + Vo$ $VIC\ min \leq Vin\ min$	$Io \leq 0.8 \bullet ICLIM \bullet \frac{Vin\ min}{Vin\ min + Vo}$ $R2 = R1 \bullet \left[\frac{Vo}{Vfb} - 1\right]$ $D\ max \geq \frac{Vo}{Vin\ min + Vo}$

1. Referring to the datasheet of this device we get : VICmin=4V,VICmax=14V
   ICLIM=1.55A. Dmax (MIN)=92%

2. Therefore we now check sequentially for these conditions:

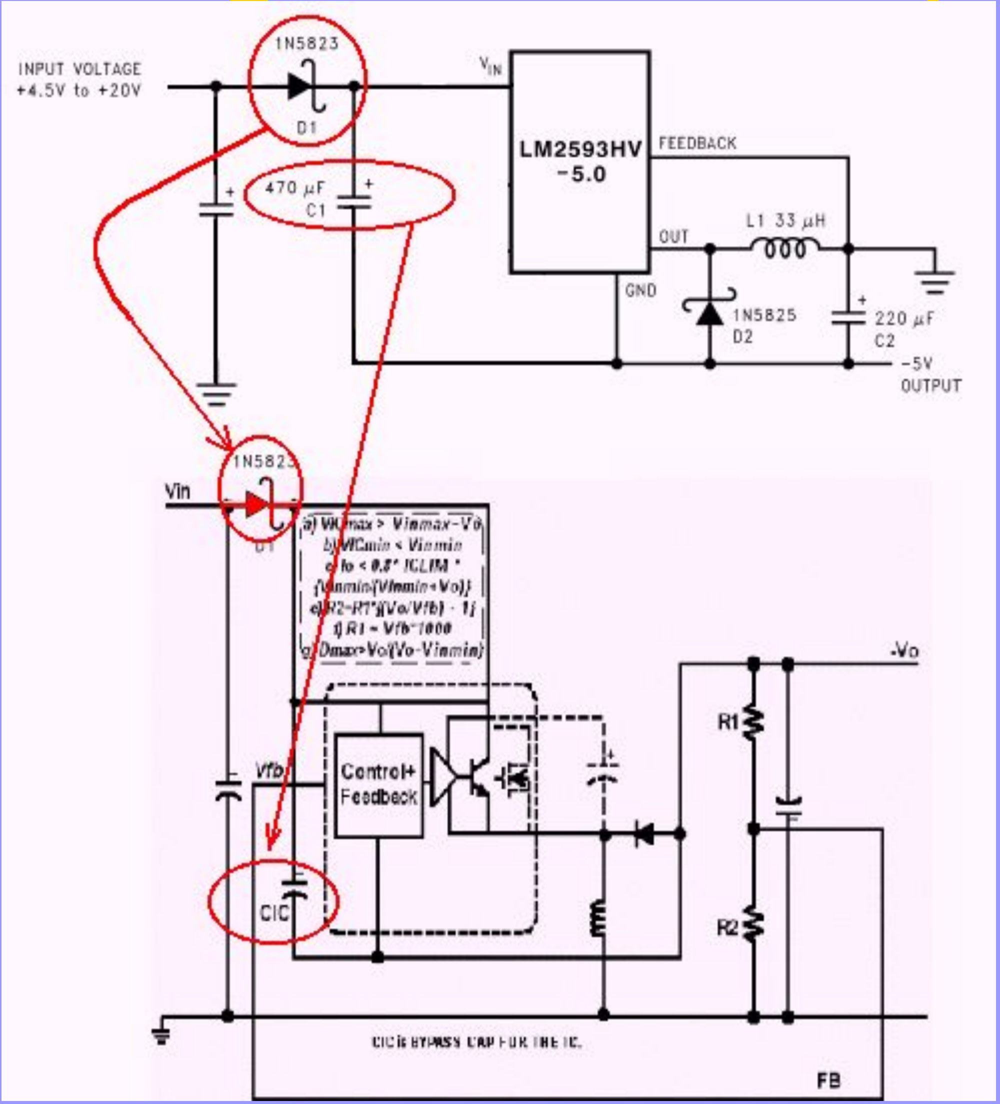
- a) VICmax>Vinmax+Vo
  14V>5.5V+5V=10.5V OK
- b) VICmin<Vinmin 4V < 4.5V OK
- c) Io< 0.8*ICLIM* (Vinmin/(Vinmin+Vo):
  0.5< 0.8*1.55*{4.5/(4.5+5)}=0.587 OK
- d) Dmax>Vo/(Vo+Vinmin)
  0.92>5/(5+4.5)=0.53 OK

Therefore the LM2651 is acceptable for the intended application.

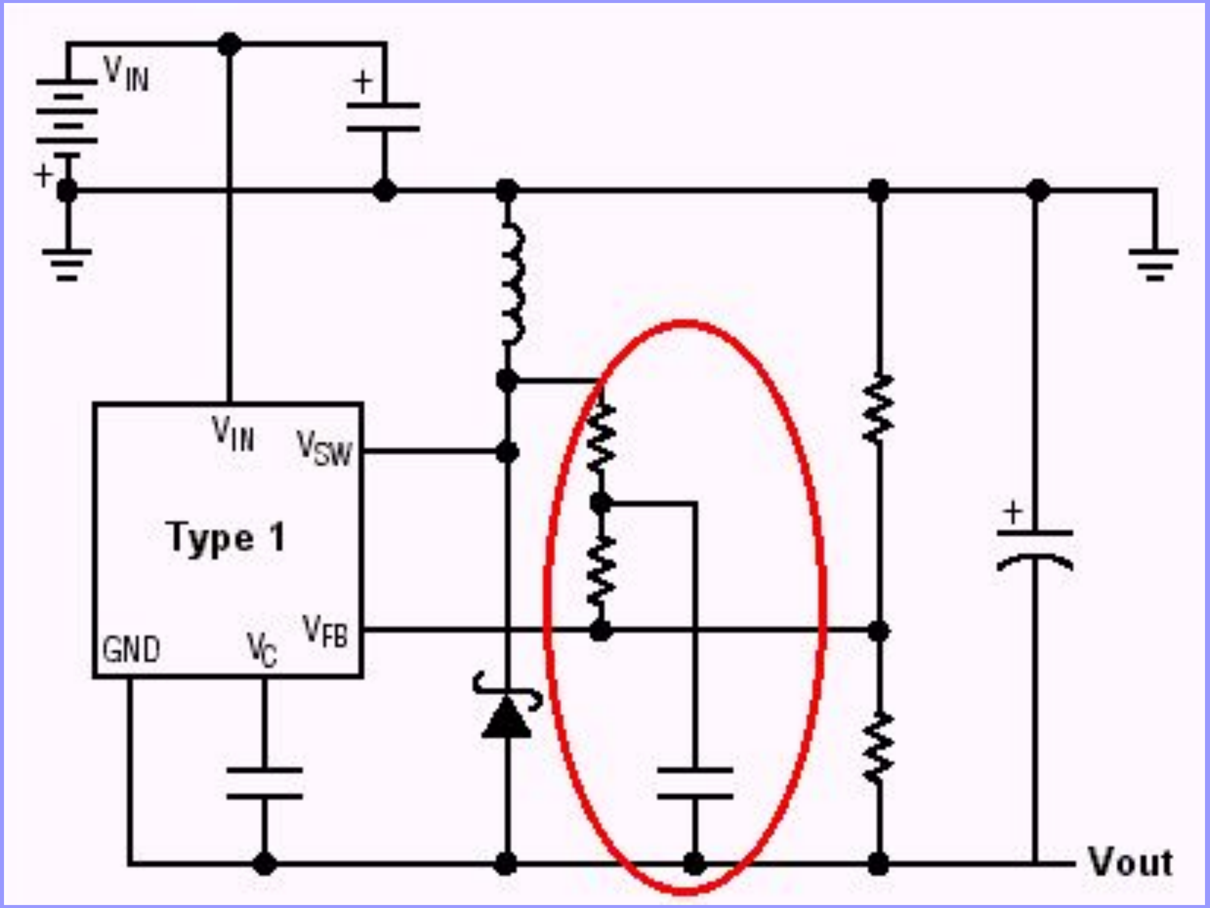
Nuances of Topology Swapping

- One of the main concerns when we jump topologies has to do with a nuance of the topologies themselves. In particular, we must remember that a Buck topology has no Right Half Plane (‘RHP’) zero, but the Boost and the Flyback/Buck-Boost do. Therefore when we try to take a Buck IC (with internal fixed compensation), we may not have the ability to tailor the crossover frequency to less than 1/4th of the RHP zero frequency as is generally recommended for avoiding this particular mode of instability. So how do we successfully take a Type 2 IC and apply it to other topologies?

Conquering the RHP Zero (1)



Conquering the RHP Zero (2)



Conclusion

- This sums up a walk through those mysterious 'hidden' applications of switchers. The average designer should have no trouble extending these principles to controllers and other types of switchers, not discussed herein. For detailed information about how to actually design switchers, please see:

References

- a) Application Note AN-1197 at http://power.national.com
- b) Application Note AN-1246 at http://power.national.com