It's a Buck; It's a Boost, No! It's a Switcher! (part one)

Technology Edge

It's a Buck; It's a Boost, No! It's a Switcher! (part one)

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We like to give everything a name or label very quickly. We probably feel we can then easily identify the object in the future, and also point it out knowledgeably to others: 'look it's a Buck, it's a Boost, it's a Buck-Boost'. In fact, as this article points out, especially when we come to integrated regulator ICs like National's "SIMPLE SWITCHER®" lineup, it pays to keep in mind that these are first and foremost Switcher ICs. They can lend themselves to various other applications beyond their primary intended function. So by labeling an IC as a Buck or a Boost IC right off the bat, we may just be missing several other opportunities.

A switchmode IC can actually be used across other topologies quite freely. For example a Buck IC can be used in a Buck-Boost application and vice-versa. This is not so puzzling once we understand that a switcher is just that: it basically switches a transistor between ON and OFF states. How we use the transistor and configure our circuit to switch a voltage across an associated inductor and how we finally route the energy to the output is not necessarily fixed. Indeed there are limitations on what all we can do, but that has more to do with how the transistor is actually driven, how the internal control of the IC is referenced, etc. It is certainly important to understand the internal construction of the IC itself, but to finally see the other 'hidden' applications needs a better (and more abstract) understanding of switcher topologies themselves.

Related literature occasionally refers to some of these hidden applications, but in a rather scattered and unintelligible way. One major problem we noticed was the way a schematic is often drawn. We came across schematics that required several right angle turns and/or several horizontal and vertical mirror reflections to make any sense of. Unless of course the IQ of the reader was genius cubed. To compound the confusion, there was rarely any attempt to even explicitly state the fact that the underlying topology had changed. In the accompanying text, it may just have been mentioned in passing that the Buck IC was being used in an 'inverting' configuration (or a 'positive to negative' converter). Go figure! What is the maximum load current in this new configuration and what is the safe input operating voltage range? Why are these different now? Is that the feedback? And how does it really work? Is the output regulation as good as it was for the original Buck? Questions like these just add to the general mystery surrounding the host of other possible applications for switchers, and to the general misery of the designer. And thereby effectively stymie the exploration of these extra possibilities.

This article tries to outline the many possible hidden uses of integrated switchmode power supply ICs, particularly the "SIMPLE SWITCHER®" lineup from National, in a clear, concise and complete way. The average designer will have no trouble in extending the same principles to all related switcher applications, even those using controllers to drive external switches.

What is 'Ground'?

We need to start with some basics. In a DC-DC converter there are two input rails (connected to the DC source) and two output rails (connected to the load). Of these, one rail is always shared between the input and the output. By convention, this common rail is designated the (system) ground. It is therefore the ground for the power stage. But there is another 'ground'. This is the IC/control ground. This may or may not always be connected to the system ground, especially if the IC is being used in a manner other than its primary intended application. So if we connect the grounds differently, there could be are other possible problems. These are mentioned briefly here at the outset because even though they are not central to the focus of this article, these may be of related importance as we explore the hidden applications, and may thus need to be solved.

a) The feedback path may not be direct anymore. The feedback voltage to the control always needs to be referred to the IC ground. But since this system ground may be at a different level voltage sensing of the output would now

need to be differential in nature. Then this difference needs to be level-shifted or 'translated' to the IC ground. There are several standard ways of doing this, all involving external components, and these will be discussed later.

b) Any ON/OFF control if required will also need to be indirectly implemented for the same reason. But the variations are extremely diverse. For example, some ICs turn the PWM stage ON if the voltage applied on the ON/OFF pin is positive (with respect to the IC ground), but in some cases the ON/OFF pin needs to be connected to IC ground to be activated. In addition the ON/OFF pin usually has a voltage rating which should not be exceeded. Therefore, the designer is going to have to independently figure out the best way to implement ON/OFF control in such cases. Of course he may not even require to turn OFF the IC, and that would be easy to do if not automatic. In this article we are not going to delve into this ON/OFF aspect further.

Note: The feedback pin also has maximum voltage ratings that should not be exceeded. Though this pin is inherently self-stabilizing, at least in steady state, the designer may need to watch out for transients during start-up or shutdown or under short circuits on the output that could damage the feedback pin. This is of concern only when the IC is used 'unconventionally', i.e. in a configuration other than its basic intended application.

Since the many different configurations can appear bewildering at first sight, it will help to point out their common threads. This will lead to a better visualization in terms of their basic building blocks and highlight all the things we can do without missing any possibilities. Therefore we will start off by some basic definitions.

Definitions: N-switch/P-switch

For bringing the myriad possibilities under smaller umbrellas, we need to make some rather unconventional definitions in this article. The reader should bear with us, as he will see that it really does help in isolating the common threads among the various hidden applications.

In Figure 1a we have indicated that a voltage of magnitude 'v' needs to be applied with respect to the Source terminal of both N-channel FETs and P-channel FETs to turn the FET ON (assuming enhancement types only). The dotted triangles (alongside the label 'v') indicate the direction of increasing voltage (in terms of magniude). We have also indicated that a voltage of magnitude 'v' needs to be applied with respect to the Emitter terminals of both NPN and PNP BJTs ('Bipolar Junction Transistor') to turn the BJT ON.

Throughout this article we will usually attempt to keep the lower voltage input rail on the bottom side of the figure and the higher voltage input rail on the top side. Further, the input is on the left side and the output on the right. These steps will help in keeping all the schematics visually appealing, easy to follow, and mutually consistent.

In Figure 1b we have show the easiest way to turn the FET or BJT OFF is to connect the gate/base to the Source/Emitter.
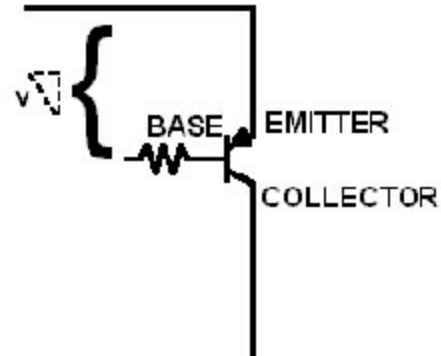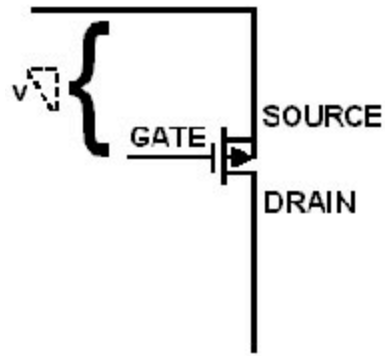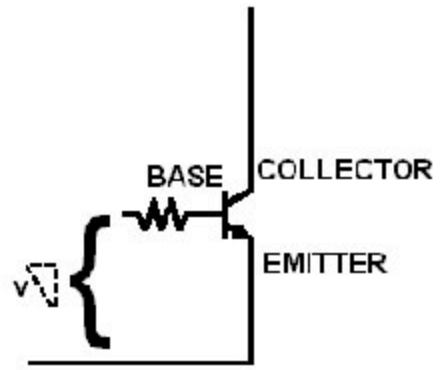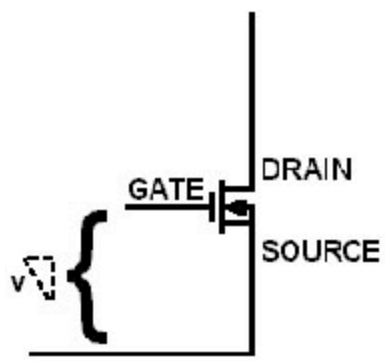
DRAIN

GATE

SOURCE

v

BASE

COLLECTOR

EMITTER

v

SOURCE

GATE

DRAIN

v

BASE
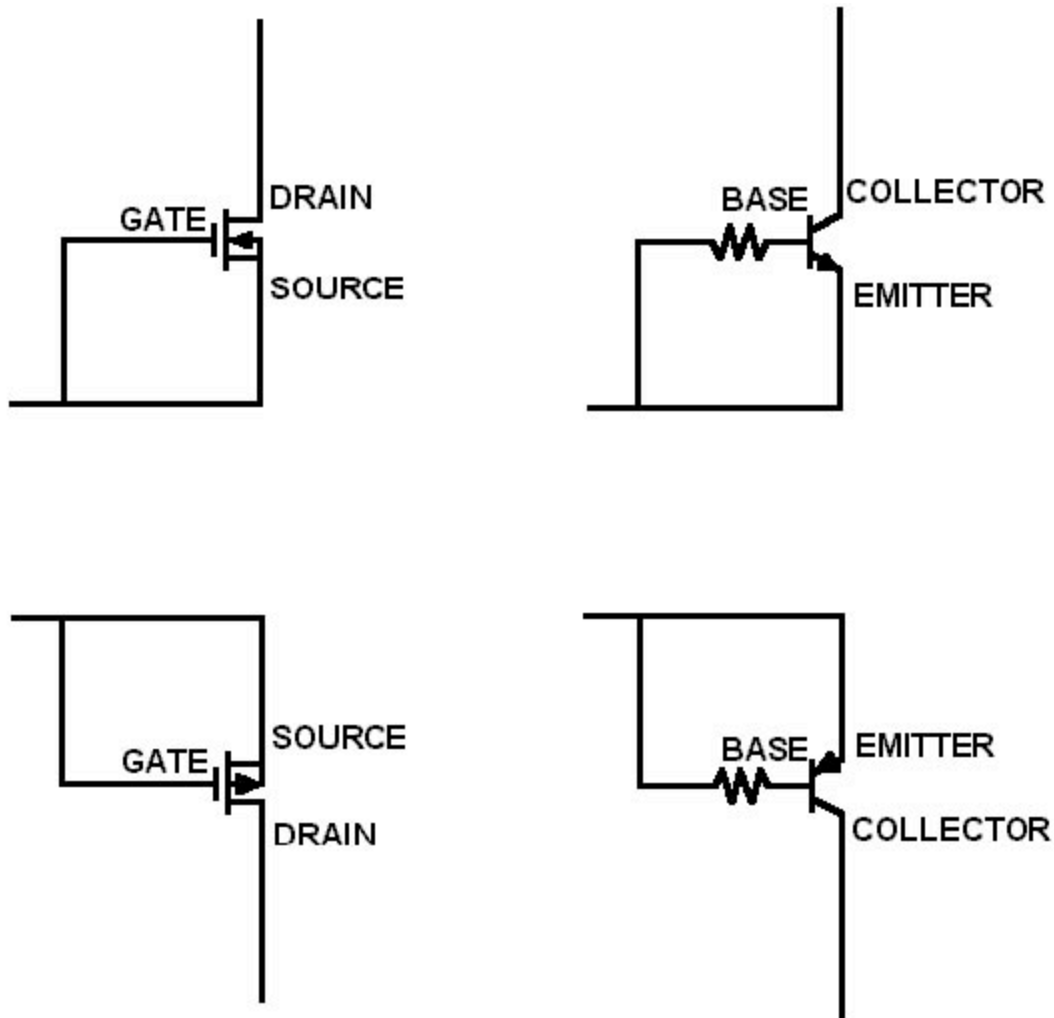
EMITTER

COLLECTOR

v

FIGURE   1a

FIGURE 1b

Because of the drive similarities, in this article we will generally talk in terms of an 'N-switch' (being either an N-channel FET or an NPN BJT) or a 'P-switch' (either a P-channel FET or a PNP BJT.

Another Definition: The 'LSD' cell

With no hallucinogenic properties at stake, the LSD cell as defined here goes a long way in understanding which hidden applications are a 'natural possibility' for a given IC and which are not. It will be shown that if we identify the LSD cell type occurring in the original intended function of a switcher IC, we can easily apply it to any other topology in which the same LSD cell type occurs, irrespective of the topology. We will also see that in some cases, by a special technique we can even make an IC perform in an LSD cell type other than its originally intended LSD cell. This is a clear alternative to talking in terms of Buck or Boost cells, which is more common in related literature. The justification here is that LSD cells, not Boost/Buck cells, are the key to understanding and tracking down the hidden applications. The topology can always change but not the LSD cell type! And this will be borne out soon.

Coming to the basic structure of power conversion circuits, in all cases we have an inductor (L), a switch (S) and a diode (D) connected to each other. This is hereafter generically nicknamed an 'LSD cell'. We will see that we can have in all just 4 LSD cell types. Two correspond to N-switches, and two to P-switches.

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 threshold voltage).**
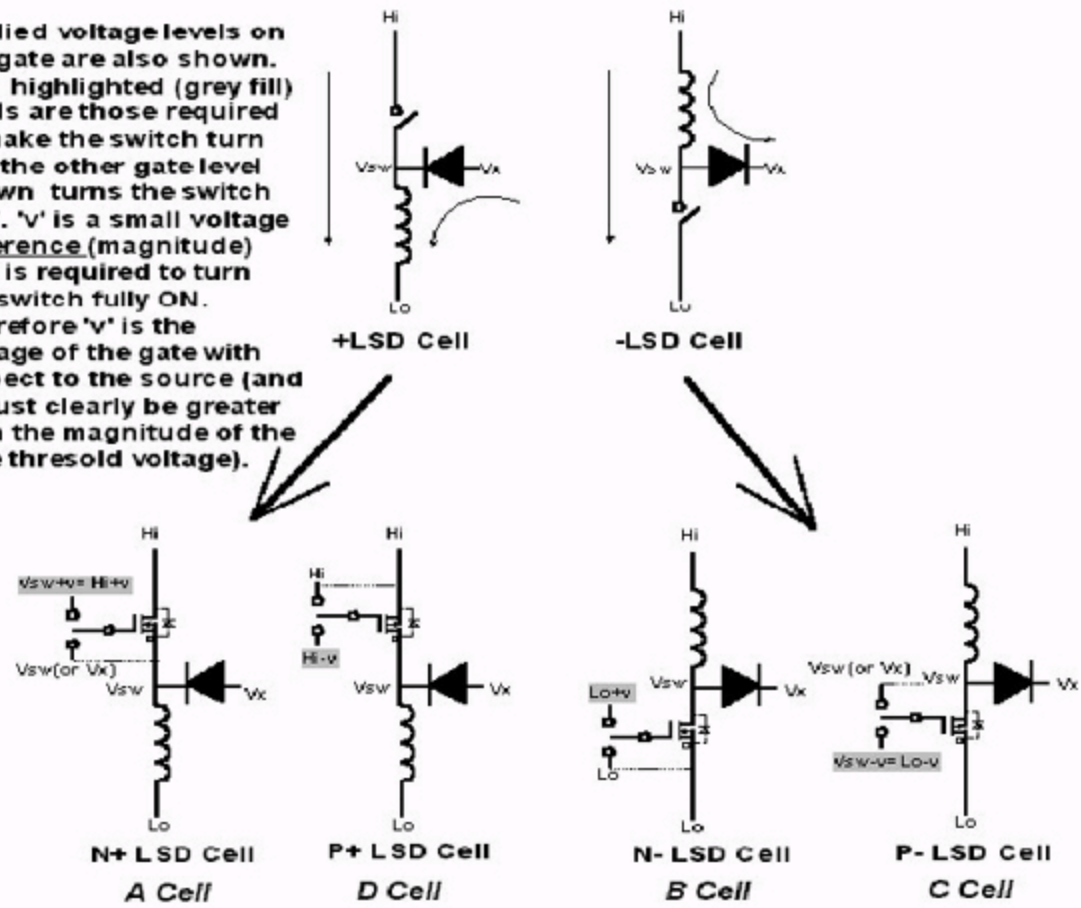
+LSD Cell   -LSD Cell

N+ LSD Cell   P+ LSD Cell   N- LSD Cell   P- LSD Cell
A Cell   D Cell   B Cell   C Cell

FIGURE 2

LSD cell types are shown in Figure 2 (the internal details of the switch are not shown here). When the switch turns OFF the current freewheels through the diode. Therefore the direction of the diode must be as indicated for each case. The 'LSD node' (the common node between the three components) is also called the 'switching node' ('Vsw') as in normal power conversion terminology. Therefore the two main cases are

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

For each case above, we can have either an N-switch or a P-switch. Therefore, in all we have four basic LSD cells at the root of any power converter. We will give these names Type A, B, C and D.

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

This is also provided in the lookup table, Table 1.

Table 1: Lookup for LSD cell descriptors

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

We introduce the following terminology from Figure 2. We need to do this because when we come to 'configurations' of the topologies we will see that the labeling of the rails keeps changing. The system 'ground' may be re-designated based on the common rail criterion discussed earlier. Therefore it is important to visualize the configurations in which the cells find themselves in, in terms of a higher voltage rail and a lower voltage rail rather than a specific label.

a) The higher voltage potential is called 'Hi' (note it is on the top side of the figure).

b) The lower voltage potential is called 'Lo' (note it is on the bottom side of the figure).

c) The common node shared by the switch, the diode and the inductor is 'Vsw' and is the 'switching node'. This voltage on this node is always 'swinging'.

d) The voltage on the other side of the diode is a DC level in all cases and it is called 'Vx' here. Therefore Vsw will equal Vx during the time the switch turns OFF, because the diode must then conduct. When a diode conducts it can be mentally thought of as 'connecting' its two terminals together. So during the entire switch OFF-time Vsw=Vx (ignoring the small forward voltage drop across the diode, and assuming continuous conduction mode). Therefore we can again refer to Figure 2 and notice that it is indicated that one way to turn the switch OFF is to connect the Gate/Base to Vx (rather than to Vsw).

Note: This implies that the 'ground pin' of control ICs can often be permanently connected to the point Vx. In some cases Vx is the output voltage rail itself. We will see this principle in action in a succeeding section.

Configurations of Switching Regulator Topologies

We note that the words 'Boost', or 'Buck' or 'Buck-Boost' always refers only to the magnitudes of the input and output voltages. So now we see the need for qualifiers like 'negative to negative', 'negative to positive' etc. to fully describe the actual configurations. The negative (or inverted) form of the modern positive to positive Boost converter is in full a 'negative to negative Boost converter'. It would convert say -12V to -48V relative to the (common) ground rail.

We have four possible configurations for each of the standard topologies. In Figure 3, Figure 4 and Figure 5 we show the possibilities for the Buck, the Boost and the Buck-Boost converters respectively. Note that we can now relate what Hi, Lo, Vsw, Vx levels really refer to in the schematic, in terms of actual circuit labels for the rails. The gate drive levels are also shown. As in Figure 2, the highlighted areas of the gate drive (gray fill) are where the FET is ON. Otherwise it is OFF. It is also indicated whether they belong to Types A, B, C or D, as defined previously.

| POSITIVE TO POSITIVE BUCK | NEGATIVE TO NEGATIVE BUCK |

N CHANNEL FET

VIN *Hi* — I — GND
VIN — A (N+LSD)
GND — + — -VIN *Lo* — -Vn *Hi*
-VIN — B (N-LSD)

P CHANNEL FET

VIN *Hi* — + — — — GND
VIN — D (P+LSD)
GND — + — — -VN *Lo* — -Vo *Hi*
-VIN — C (P-LSD)

FIGURE 3

NEGATIVE TO NEGATIVE BOOST	POSITIVE TO POSITIVE BOOST

N CHANNEL FET

GND

+

−

-VIN
Lo

-VIN
-Vo

-Vo
Hi

A
(N+LSD)

YIN
Hi

+

−

GND

VIN

Vo
Lo

B
(N-LSD)

P CHANNEL FET

GND

+

−

-VIN
Lo

-VIN

Vo
Hi
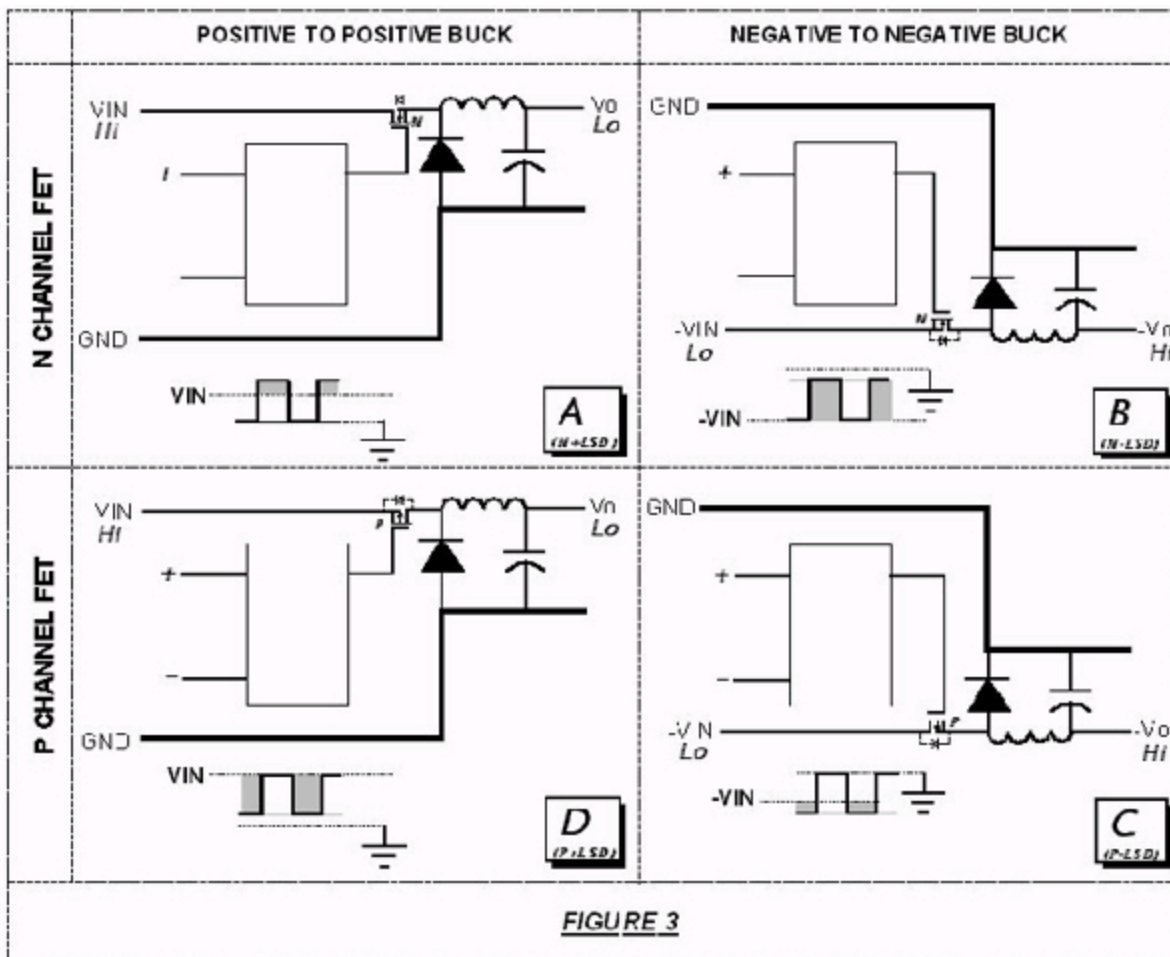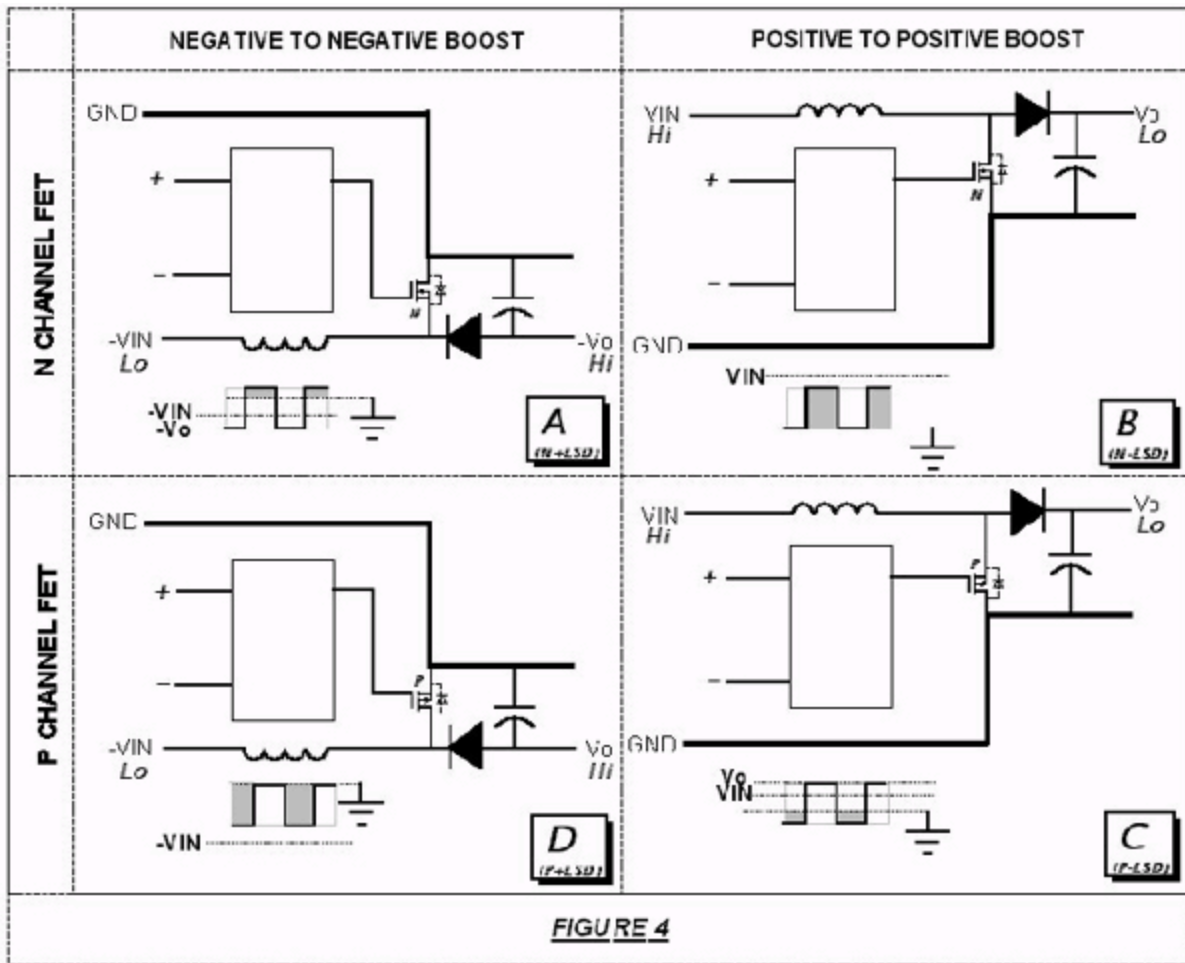
D
(P+LSD)

VIN
Hi

+

−

GND
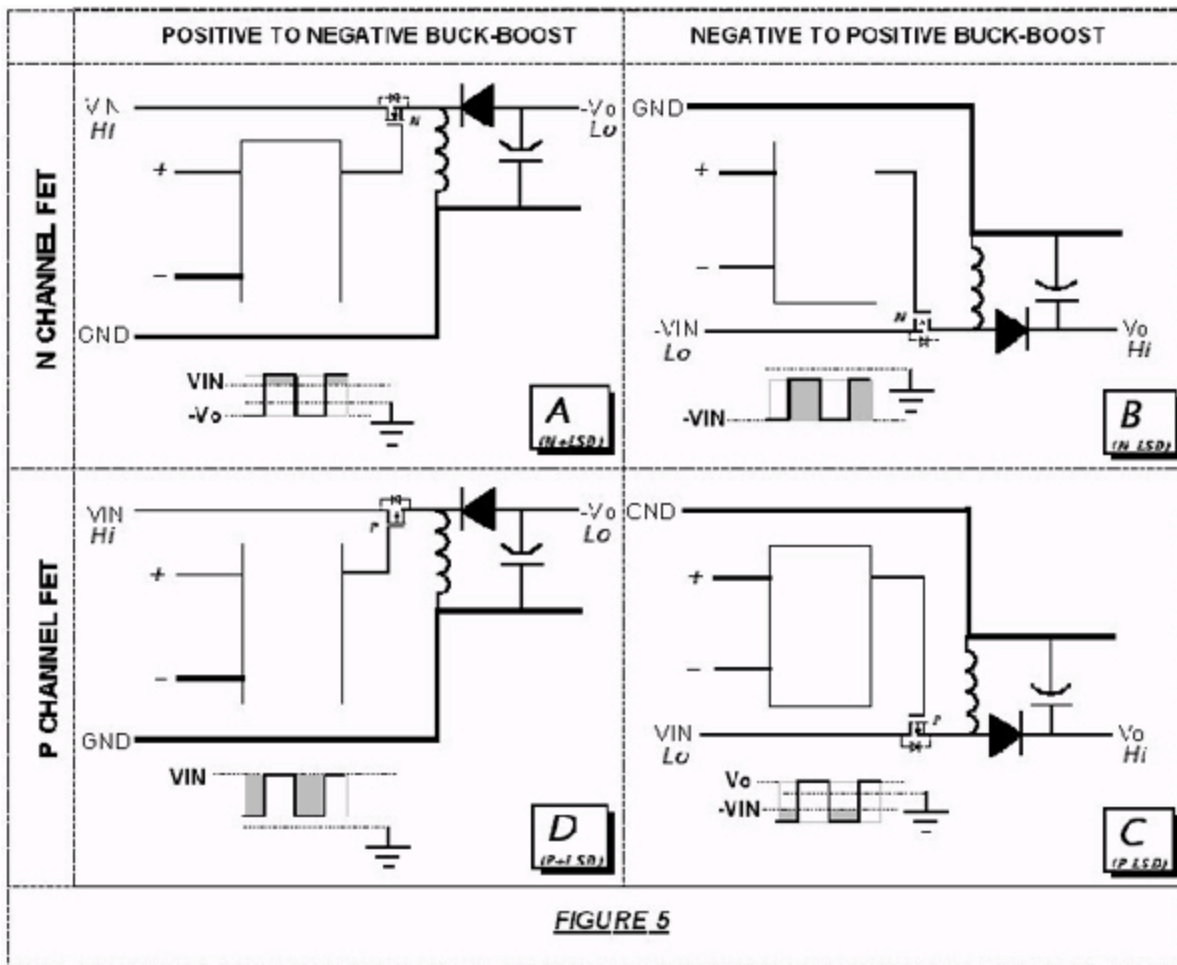
Vo
VIN

Vo
Lo

C
(P-LSD)

FIGURE 4

FIGURE 5

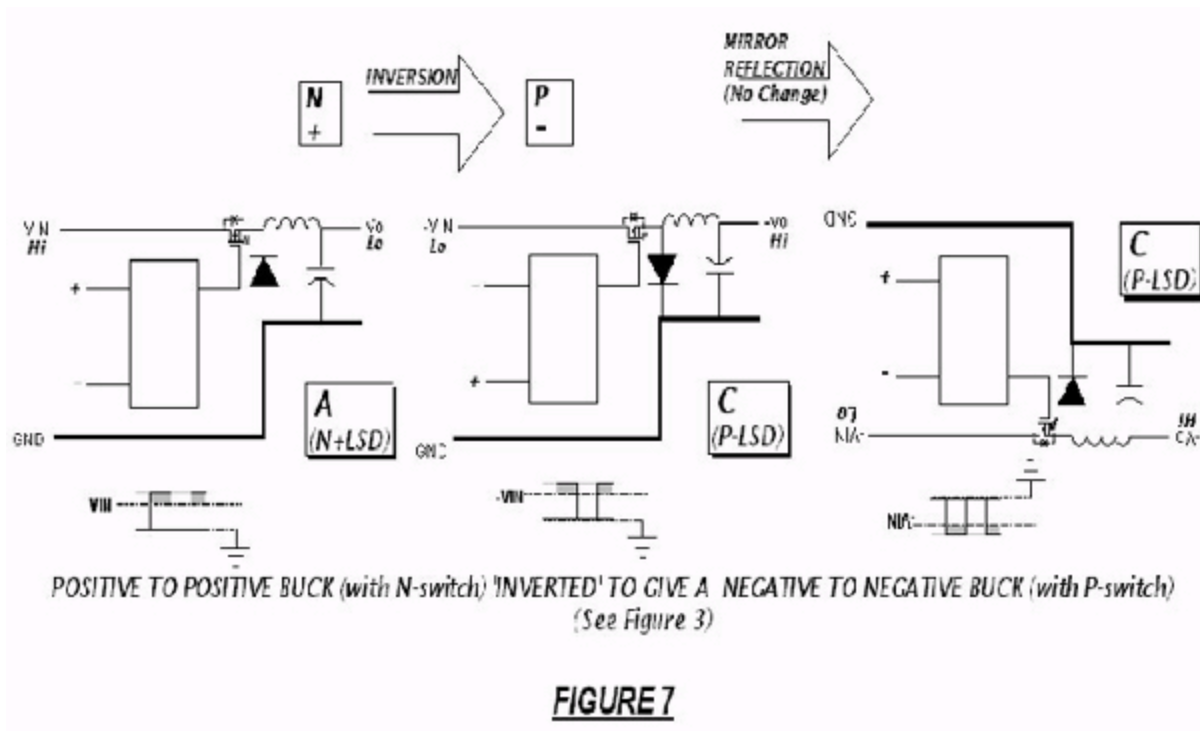**N-Switch Configurations to P-Switch Configurations**

We saw above that there are different possible 'configurations' of a given topology. This means that though it does not amount to a fundamental (or topological) change, this does change the schematic significantly.

Nowadays it is customary to call the lower input rail as the system 'ground' ('negative ground' convention). But for many years it was commonplace to refer to the upper rail as the ground ('positive ground'). Though there are some practical EMI vs. thermal management tradeoff issues also related to the typical switch/diode structures, it is almost by sheer tradition that many telecom systems are still 'positive ground'. We initially feel that in going from a positive ground schematic to a negative ground schematic, it may just be a simple matter of re-labeling in terms of which rail we decided to call 'ground', i.e. the upper input rail or the lower input rail. But when we consider the fact that there is a common rail between the output and the input of a switching converter, and it is this rail that needs to be the designated the 'ground' all the way from the input to the output, we realize that the circuit schematic really needs to change.

Yet engineers learnt quickly to do so. The method to proceed is an old one: to draw the ground negative circuit from a ground positive circuit (and vice versa) we simply invert all circuit polarities. So '+' becomes '-' and 'hi' becomes 'lo' (and vice versa respectively). And for example the anode (positive terminal) and cathode (negative terminal) of a diode are interchanged, which is equivalent to just reversing the direction of the diode. See Figure 6 for an example of how to 'invert' various components (shown with some typical voltage levels). Note in particular how a switch is inverted. The pin assignments are NOT changed (Drain is still a Drain etc.), but the structure is inverted (for example from an N-channel FET to a P-channel FET).
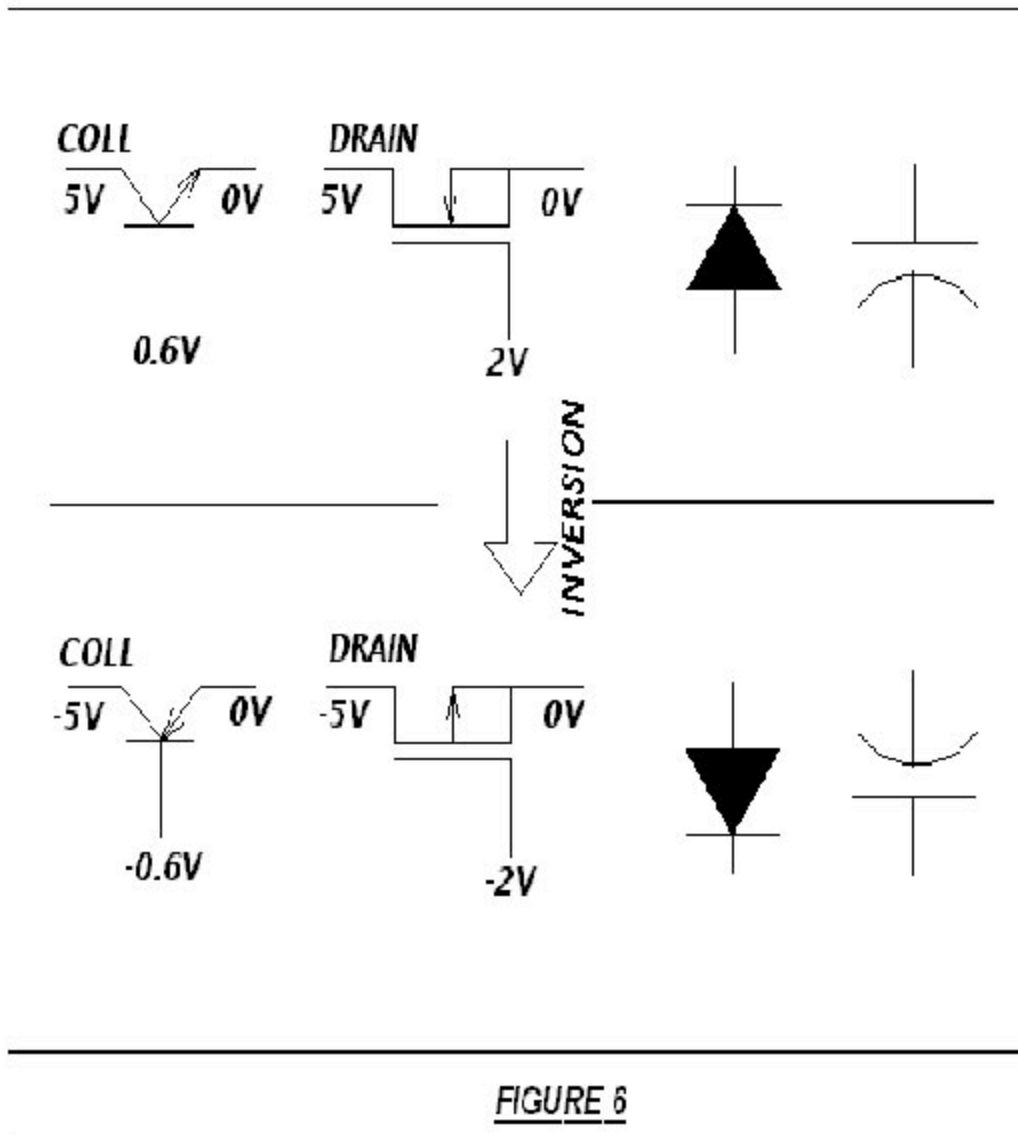
FIGURE 6

In Figure 7 we perform 'inversion' on a N+ Buck circuit (type A) and show that it leads directly to a P- Buck circuit (type C). If it is not so obvious, we can flip the circuit vertically ('reflection') to put it in line with our declared goal of visualizing all circuits with higher input voltage rails on the top side of the page and lower voltage rails on the lower side. Comparing it with Figure 3 we will see that indeed we have generated not only the P- circuit but also the required gate drive levels.

POSITIVE TO POSITIVE BUCK (with N-switch) 'INVERTED' TO GIVE A NEGATIVE TO NEGATIVE BUCK (with P-switch)
(See Figure 3)

FIGURE 7

Therefore in all cases (for any topology), 'inversion' amounts to changing the LSD descriptor as follows:

N ß> P + ß> -

In terms of the simplified lookup table for Types a, B C and D, inversion would amount to changing the configuration type (for any given topology) according to:

A ß> C B ß> D

This implies that if we study the more common N-switch configurations we can quickly generate the corresponding inverted P-switch version (and vice versa if we wish).

Example1: If we need to create a schematic for a negative to positive Buck-Boost using a P-channel FET (Type C from Figure 5), we can start by generating a positive to negative Buck-Boost schematic using an N-channel FET (Type A from Figure 5) and then invert it.

Keep in mind that N-switches are generally preferred as they reduce die size for a given Rds/Vce_sat as compared to P-switches. Therefore we will now focus exclusively on IC's using N-switches only.

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Next issue - Part 2: It's A Switcher

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