Cuk-Based Converter Concepts

Part 1: Basic Converter Configurations with Ripple-Current Steering

by Dennis L Feucht

The essence of the converter idea introduced in the 1970s by Slobodan Ćuk (rhymes with *book*) of Cal Tech is that of *ripple-current steering*. The idea is to operate a transductor (see inset box for terminology) at the boundary between transformer and coupled-inductor operation.

This is done by applying the same (or nearly the same) voltages to both windings simultaneously. What is the point to this? It effects a magnetic bootstrapping, whereby the externally voltage-driven winding, which would undergo an increase in current, is opposed by the magnetic flux of the other winding. If done right, the two effects cancel, leaving the current in the externally driven winding constant. Elimination of current ripple in a transductor winding is ideal in converter design, and current-ripple "steering" using a second winding essentially accomplishes it.

Coupled Inductors Versus Transformers

Flyback converters use magnetic devices with at least two windings in a different way than do forward converters. In a flyback, the primary winding supplies energy to the magnetic field during the on-time of the switch. Then during off-time, the field delivers energy to the secondary circuit. All of the transferred energy is stored in the magnetic circuit (the core, mainly), as an inductor. But instead of having only one winding, the second winding allows multiple electrical access to the magnetic circuit.

A transformer transfers energy directly from the primary to the secondary winding without storing it in the magnetic circuit. To do this, current flows simultaneously in both windings, and their fluxes are of opposite polarity and cancel. Essentially no energy is stored in the magnetic circuit. For forward converters, the primary and secondary circuits conduct at the same time.

Another way to describe the difference is that the mutual coupling to the magnetic circuit in a coupled inductor is positive in that the fluxes generated by the windings are of the same polarity and add, causing the flux to have a non-negligible value and magnetic energy to be stored in the core. For a transformer, coupling is negative in that the fluxes oppose and cancel, leaving a negligible net flux in the magnetic circuit.

Yet another way to distinguish – from an electric circuit standpoint – is that transformers have no net unipolar (dc) currents in their windings while inductors usually have a large unipolar component. Transformers are driven bipolar while inductors have unipolar currents. All inductive devices require bipolar voltage drive for flux balance, just as capacitors require bipolar current drive for charge balance.

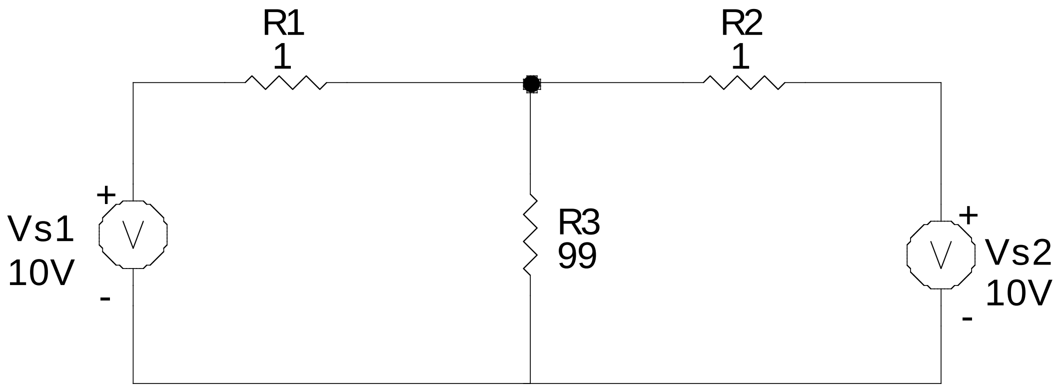
How magnetic devices are designed depends on whether they are to be used as inductors with large static or average (dc) and small varying (ac) current components, or transformers, with only varying currents. High-frequency switching losses from these varying currents require low-loss cores at switching frequencies, and these are generally ferrite cores. But if the varying component is small, powdered-iron cores (or variations on them) are more optimal. The losses from varying currents in them are greater (requiring small varying currents), but their flux saturation values are three to five times higher than ferrites, and can maintain their inductance values at higher currents.

Flyback coupled-inductors are, nevertheless, usually designed with ferrite cores because their varying currents are large, though they are unipolar. This is not necessary true for continuous-current mode (CCM) flybacks, however.

Cuk-derived converters use the magnetic device at the boundary between inductor and transformer. The static (dc) component of currents in the windings aid, like an inductor. But the varying components oppose, like a transformer. What is needed is a general word for magnetic devices with multiple turns that includes both transformers and coupled inductors. How about *transductor*?

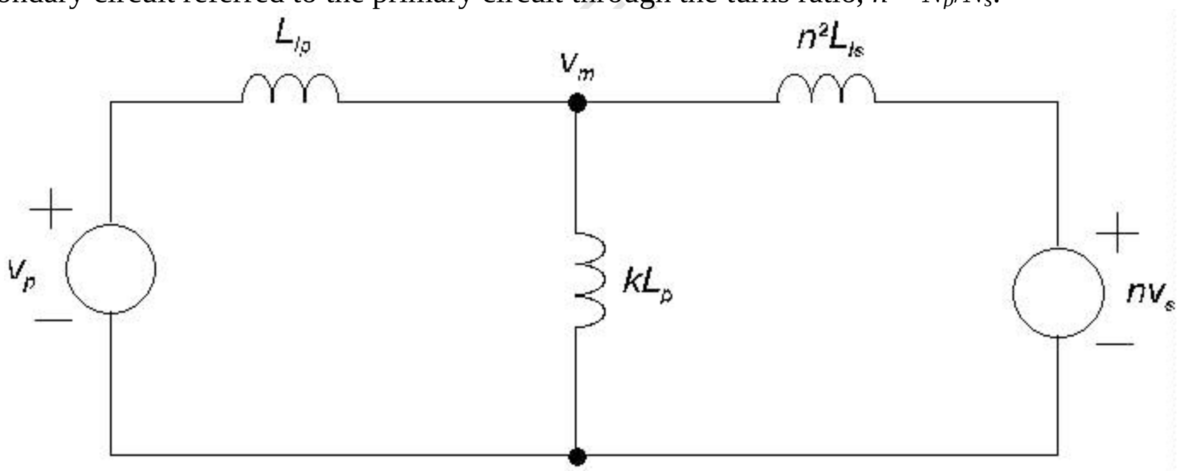
The Ripple-Steering Concept

To understand how ripple steering works, we will start with something more familiar than transductor circuits: a resistive divider circuit with two equal voltage sources driving a common resistor, R_3, as shown.



R_1 and R_2 are much smaller than R_3 and connect to it at the center node. Consequently, a slight variation in either V_{s1} or V_{s2} will cause a large change in the fraction that each source supplies to the common branch, R_3. If V_{s2} were to increase to 10.1 V, it would raise the voltage at the center node from a balanced value of 9.95 V to 10 V, causing the current through R_1 to be zero. All R_3 current would then be supplied by V_{s2}. In effect, V_{s2} has bootstrapped the V_{s1} branch of the circuit.

Similarly, the leakage inductance values of transductor windings are much smaller than the magnetizing inductance, L_{mp}, referred to the primary side (hence the subscript p). The transductor model is shown below with secondary circuit referred to the primary circuit through the turns ratio, $n = N_p/N_s$.



The secondary voltage source, v_s, induces $n \cdot v_s$ across the primary winding. Similarly, v_p induces v_p/n across the secondary winding. The combined fraction of both that appears across the magnetizing inductance, $L_{mp} = k \cdot L_p$, is v_m. The basic transductor equations are given below, where k is the coupling coefficient between windings:

$$n = \frac{v_p}{v_s} = \frac{i_s}{i_p}$$

$$n^2 = \frac{L_p}{L_s} = \frac{L_{mp}}{L_{ms}} = \frac{L_{lp}}{L_{ls}}$$

$$L_{mp} = k \cdot L_p \,;\, L_{ms} = k \cdot L_s$$

$$L_{lp} = (1-k) \cdot L_p \,;\, L_{ls} = (1-k) \cdot L_s$$

The above circuit can be solved for v_m by applying voltage superposition:

$$v_m = \frac{k \cdot L_p \parallel n^2 \cdot L_{ls}}{k \cdot L_p \parallel n^2 \cdot L_{ls} + L_{lp}} \cdot v_p + \frac{k \cdot L_p \parallel L_{lp}}{k \cdot L_p \parallel L_{lp} + n^2 \cdot L_{ls}} \cdot (n \cdot v_s)$$

Then solving for v_m and simplifying:

$$v_m = \left(\frac{k}{k+1}\right) \cdot (v_p + n \cdot v_s)$$

For $v_m = v_p = v_s$, then:

$$v_p \cdot \left(1 - \frac{k}{k+1}\right) = \frac{k}{k+1} \cdot n \cdot v_p$$

Solving for n:

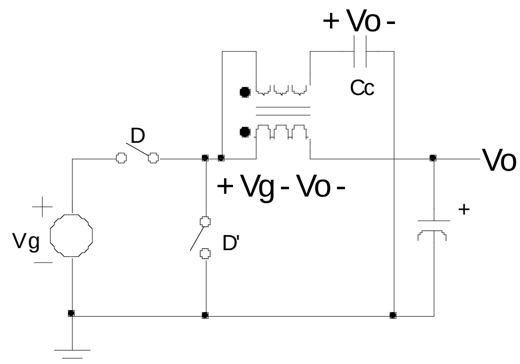
$$n = \frac{1}{k}, i_p = 0$$

By increasing n slightly from one to $1/k$, the voltage induced by v_s will increase v_m to v_p, thereby *bootstrapping* L_{lp}, just as R_1 was bootstrapped in the resistive circuit. Because the voltage at each end of L_{lp} is the same, its inductance is, effectively, infinite. Consequently, all variations in magnetizing current, (through L_{mp}) due to a varying v_p are supplied from the secondary winding source. By symmetry, setting $n = k$ causes the secondary-winding current to become constant (varying $i_s = 0$) while the primary source supplies the magnetizing-current variations.

This effect can be desirable because (for $n = 1/k$) it results in constant (dc) primary current. Noisy ripple current due to switching does not appear at the converter input but is diverted instead to the secondary winding internal to the converter. However, typical values of k are slightly less than one, and turns ratios of *nearly* 1:1 may not be easy to wind. One simplification is to use a 1:1 transformer and add a small additional inductance in series with the primary winding. This effectively increases L_{lp} so that the same secondary-winding conduction of magnetizing current is obtained with $n = 1$. Prototype transductors can be designed with primary-winding taps around $n = 1$ and selected empirically for minimum current ripple, thereby taking into account the parasitic series inductance in both primary and secondary circuits for a given converter layout.

Current-Ripple Steering For Basic Converters

The three basic converter configurations can be enhanced by ripple steering, by changing their inductors to transductors, as shown below, for the CP (buck) configuration.

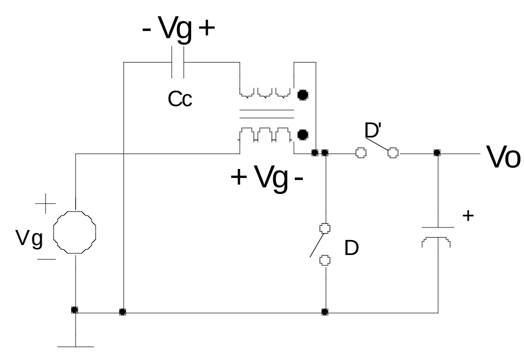


In steady-state operation, the ripple-steering capacitor, C_c, will charge to an average of V_o. During the on-time (D switch closed), the transductor voltage is $V_g - V_o$. The secondary winding has V_o applied by C_c to its right terminal and V_g to its left terminal. The resulting voltage across the secondary winding is consequently, $V_g - V_o$, the same as applied to the primary winding. Consequently, the transductor operates at the boundary between transformer and coupled inductor. With slight adjustment of n, the magnetizing current ripple can be diverted to the secondary winding, charging C_c, while the output current remains constant, thereby eliminating output current ripple. In practice, some ripple will occur because C_c is not infinite in value and voltage ripple occurs across it.

During the off-time (D' switch closed), the applied inductor voltage is $-V_o$ (dotted end to output). The voltage applied to the secondary is now also the same, and ripple steering applies throughout the complete switching cycle. During the off-time, C_c discharges to make up for the otherwise decreasing current of the primary winding because of the defluxing magnetizing inductance of the transductor. Instead of a downward ramping output current waveform, it is held constant by current transferred from secondary to primary from C_c.

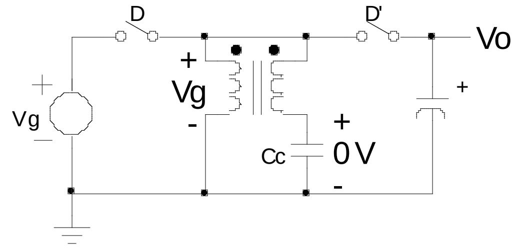
The overall effect of the additional winding and C_c is to buffer the ac component of the inductor current as C_c current, by diverting the current ripple to C_c through the magnetic coupling of the transductor. This basic ripple-steering behavior is the basis for the Cuk-derived converters.

Now apply ripple steering to the CA (boost) configuration. The resulting circuit is shown below.



For the CA, the static voltage across C_c is V_g, as shown. The on-time primary voltage is also V_g. During off-time, it is $V_g - V_o$. This coincides with the voltage applied to the secondary during the off-time. The ripple-steering behavior is similar to the CP case. With the correct turns ratio, magnetizing current is diverted to the secondary circuit.

And what of the third and last configuration, the CL? A minor chord is struck in the ripple-steering background music, as the circuit is unveiled below.



The applied voltages on primary and secondary sides are the same during both on- and off-times, resulting in the required flux balance. However, the static voltage across C_c is now 0 V! For steady-state operation, this is the same as shorting C_c and connecting the bottom terminal of the secondary winding to ground. This places both windings in parallel, and is the equivalent to a single-winding inductor. The resulting circuit is the original CL converter without ripple steering. On the per-cycle time-scale, there is still ripple voltage across C_c, though its average voltage is 0 V. Consequently, ripple steering should still occur and the desired effect realized.