Technical Bulletin

BULLETIN FC-S4

Step-gap "E" core swing chokes

Improved regulation and higher efficiency are possible when operating at minimum current levels

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When designing the output inductor of a typical switching power supply, operation at minimum or zero load current must be considered. At minimum loads, the current through the inductor can become discontinuous for portions of a cycle. When this happens, circuit feedback can cause the output voltage to increase considerably, resulting in unsatisfactory regulation.

Figure 1 has a schematic of a typical switching regulator. Voltage (E_{in}) is unregulated dc fed to a transistor. The output of the transistor is a series of pulses. and the frequency and/or pulse width is a function of the IC feedback network. The pulses are then fed to a filter network which turns the pulses into a regulated dc output.

The inductor's current as shown is essentially a triangular wave shape superimposed on dc. As the load resistance increases, the dc through the inductor decreases until it nears zero. At this load condition, the inductor's wave shape is distorted because part of its wave tends to be a negative value. Since the transistor can't have a negative collector current, the average dc is less than the value required by the load or constant output voltage, and the output voltage tends to drop. The feedback then adjusts the transister for more voltage, and the power supply loses its regulated output.

One method to avoid this situation is to use a resistor across the output. This maintains a minimum current flow through the inductor even at zero load currents. However, this preload resistor wastes power and lowers the overall efficiency of the power supply.

Another method is to use a swing choke for the power inductor. A swing choke provides the required inductance to smooth out the ripples at *both* high and medium load currents without reducing efficiency. At near zero load current, this same choke assumes a much larger induc-

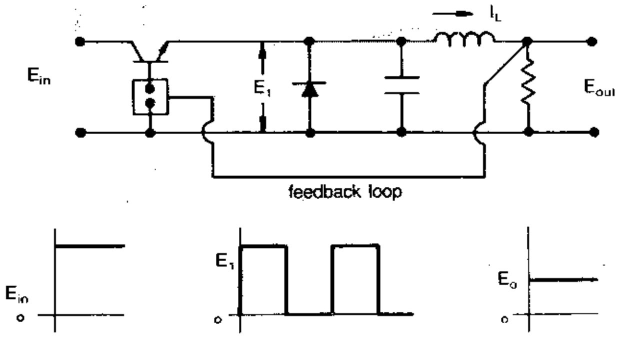

Figure 1(a).
Switching regulator schematic

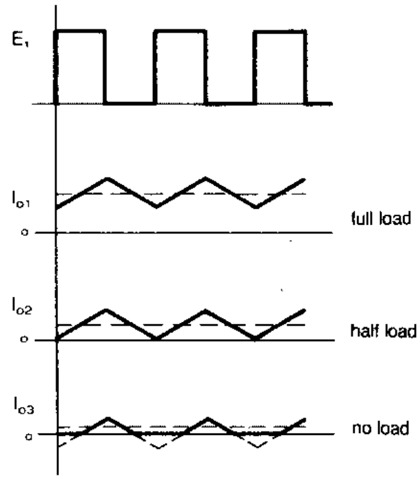

Figure 1(b).
Output waveforms

tance, preventing the current from becoming discontinuous during this phase of operation. It thus performs a similar function as the preload resistor except it does so more efficiently. A small resistor across the load may be necessary in addition to the swing choke; however, its resistance is higher and the energy waste is less than in a unit without a swing choke.

Two Inductors In One

Characteristics of a typical swing choke are shown in **Figure 2.** As noted, the inductance and effective permeability at zero and small bias currents are four times the value at the higher currents. This component gets its name from the fact that the inductance changes, or "swings", from high to low values as required when the current increases.

The swing choke in Figure 2 was made using the ferrite "E" core shown in **Figure 3.** The center leg has two gaps; one gap (G_1) is approximately 0.004"; the second gap (G_2) is 0.090" and covers about three-fourths of the width of the center leg. This component is often called a "step-gap" E core.

The inductance of this core is relatively high without any dc flow because gap G_1 is small. As dc begins to flow, the core at gap G_1 quickly becomes saturated because of its small cross- sectional area. Since this part of the center leg is saturated, its permeability is nearly "one"; therefore, it becomes part of the air gap.

As dc is increased further, gap G_2 takes over, and the core now behaves as if it has an air gap of 0.090", resulting in a reduced inductance. The current can be increased substantially over this amount with only a slight drop in inductance. As shown in Figure 2 the load current can be increased nearly 5 times that required to saturate the core at G_1 before the whole center leg becomes satured and the inductance is effectively reduced.

Many variations can be made to the shape of the curve in Figure 2. By altering both gap depths and width of the E core center leg step, the A_L versus dc bias curve can be changed to suit circuit designs and output requirements of specific switching power supplies.

Core Selection And Gaps

In order to design a swing choke, it is first necessary to establish the desired curve of inductance versus output current, similar to that shown in Figure 2. From this information, the inductor's required maximum energy storage can be calculated with the following equation:

$$ES = \tfrac{1}{2} L I^2, \qquad (1)$$

where ES is the amount of energy storage, L is the inductance at the maximum peak current of the design, and I is the value of maximum peak current through the inductor. The amount of energy storage required determines the core size and the depth of gap G_2.

Most core manufacturers present information for the core selection and depth of gap for particular value of energy storage One selection method is from a Hanna curve. This method selects the core size and depth of gap from a single curve. In addition to the Hanna curve, Magnetics also presents a series of charts for more detailed core selection (Reference 1). It should be noted that these charts are quite conservative and the selected core can often store more energy than calculated for the original selection.

The Hanna curve gives information on the gap size while the Magnetics charts give the A_L value. To relate the two, the following equation can be used:

$$l_g = \frac{.4\pi \times 10^8 \times A_e \cdot}{A_L} - \frac{l_e}{\mu m} \qquad (2)$$

where l_g is the required depth of gap G_2 in cm, A_e is the effective core area in cm², l_e is the effective core path length in cm, μm is the relative permeability of the core material and A_L is the inductance in mH/l,000 turns.

The Second Gap

Once the core and depth of gap G_2 have been selected, there remains the problem of designing the width of the step in the gap and depth of gap G_1. To accomplish this the following equation can be applied:

$$\sum \frac{l_g}{A_g} = \frac{.4\pi N^2 \times 10^8}{L} - \sum \frac{1}{\mu m} \times \frac{l_c}{A_c} \qquad (3)$$

where l_g is the effective length of gap G_1 in cm, A_g is the effective area of gap G_1 in cm², N is the number of turns, L is the inductance in Henries required at dc = 0, μm is the relative permeability of the core material, l_c is the effective path length

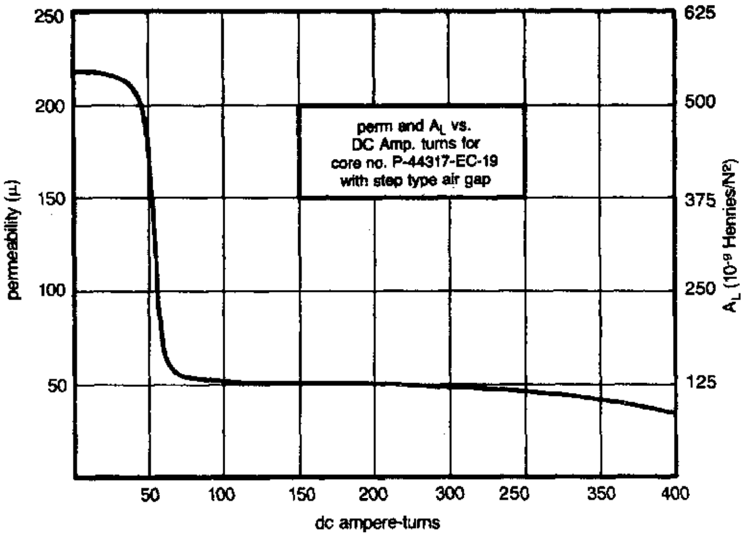

Figure 2.
Characteristics of a typical swing choke

of the core in cm and A_c is the effective area of the core in cm².

The solution of this equation for a core with one air gap is relatively simple. However, the solution for a step gap is complicated and involves several assumptions concerning the flux flow within the gap and within the part of the core closest to the gap.

Step Width

A more practical solution is first to make the width of the step such that its area is one-fourth the area of the whole center leg.

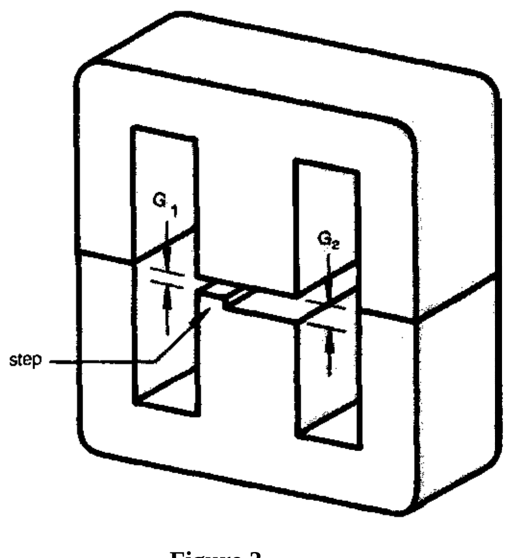

Figure 3.
Swing choke core structure

The width of the step governs the amount of magnetizing field of ampere-turns required to reduce the inductance from its high initial value. It is common practice to have the inductance begin to drop at a magnetizing force which is 20% of the maximum dc field present at full load.

To increase the amount of magnetizing force at which the inductance is to be reduced, it is necessary to increase the amount of area in the step. This is not a direct proportion, however, with trial and error, desired results can be obtained.

The depth of gap G_1 (or l_g) can also be determined from the solution of equation 3. However, for the reasons mentioned previously, it is not calculated but arrived at by trial and error. This gap is usually no more than a few thousands of an inch, and will produce a ratio of maximum inductance to the inductance at high dc values of approximately 5-to-1, a value which is usually adequate.

If designing a step-gap E core proves too difficult, the core manufacturer can usually help. All that is required is for the user to furnish the core manufacturer a curve of inductance versus dc bias similar to Figure 2.

The swing choke is an old technique that has been revived for switching power supplies. It improves power supply efficiency at little or no extra cost. The design is not as straight forward as might be desired and does require some "cut-and-try" operations to obtain the desired response. Since the resultant extra efficiency is relatively free, the use of this technique is increasing and is expected to be found in many future switching power supply designs.

References:

[1] Bulletin SR-1A, "Inductor Design in Switching Regulators", Magnetics, Butler, PA.

[2] Catalog FC-601, "Ferrite Cores", Magnetics, Butler, PA.

Sample Quantities of Step-Gap "E" Cores to meet your needs are available from the factory. See address below.

MAGNETICS LITERATURE

General Information
- TID-100—Power Transformer and Inductor Design
- CG-05 Frequently -Asked Questions About Magnetic Materials and Their Answers
- PS-02 Cores for Switched Mode Power Supplies
- SR-1A Inductor Design in Switching Regulators

Ferrites
- FC-601 Full line Ferrite catalog
- FC-S1 Ferrite Material Selection Guide
- CG-01 A Critical Comparison of Ferrites with other Magnetic Materials
- CMF-2.1 Common Mode Filter Inductor Design Software Diskette
- MMPA Standard Specifications for Ferrite Pot Cores
- MMPA Standard Specifications for Ferrite U, E, I Cores

Tape Wound Cores
- TWC-500 Tape Wound Core Manual
- TWC-S1 Fundamentals of Tape Wound Core Design
- TWC-S2 How to Select the Proper Core for Saturating Transformers
- TWC-S3 Inverter Transformer Core Design and Material Selection
- TWC-S5 Composite Tape Cores
- SR-4 Mag Amp Control in Switching Regulators
- RC-1 Magnetic Cores for Ground Fault Detectors

Bobbin Cores
BCC-1.1 Design Manual
BCD-1.1 Design Manual (catalog) Diskette

Cut Cores
- lMCC-100 Nickel-Iron, Supermendur and Amorphous Alloy Cut Cores Catalog

Powder Cores
- MPP-400 Molypermalloy Powder Core Design Manual
- HFC-1.0 High Flux Powder Cores
- HFD-1.0 High Flux Cores (catalog) Diskette
- KMC-2.0 Kool Mμ® Powder Cores
- KMD-2.0 Kool Mμ Cores (catalog) Diskette
- PCD-2.3 Inductor Design Software Diskette

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