Utilizing Ripple Steering in Forward and Flyback Converters and Input Filters

UTILIZING RIPPLE STEERING
IN FORWARD AND FLYBACK CONVERTERS
AND INPUT FILTERS

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Abstract

This paper will show that current ripple steering can be applied to a forward converter which will eliminate the pulsating input current by steering it to an internal ripple winding. A similar technique can be used to steer both the input and output pulsed current of a flyback converter by employing two internal ripple windings on the main flyback transformer. The author will also show that ripple steering can be incorporated in an input filter to aid in meeting FCC or Mil-STD-461 specifications.

Introduction

One of the major problems in using a forward converter is the pulsating input current. This pulsating input current requires a large input capacitor to handle the rms current and an EMI filter which has to filter out the large harmonics of the pulsed current.

In a flyback converter, pulsating current appears both on the input as well as the output, causing a similar problem on the input section as the forward converter. The output pulsed current requires large bulky capacitors to handle the rms currents and a high frequency filter to minimize the ripple to an acceptable level.

A solution to the problems of pulsating input and/or output current is to include ripple steering windings, allowing the pulsed currents to be internal to the converter and DC currents to appear on the input and/or output of the converter.

The ripple steering technique applied to the input filter has reduced the switching frequency and its harmonics (up to 1MHZ) by up to 10dB, thereby reducing the size and weight of the EMI filter.

Basic Principles of Ripple Steering

Ripple steering for output filtering has been around for many years but remains a mystery due to the many complex explanations. It is hoped that this paper will demystify and simplify ripple steering.

Armed with the basic knowledge, we will develop ripple steering techniques for forward/flyback converters and input filters.

Ripple Steering in Output Inductor

In order to develop the equations for ripple steering, one must include the leakages associated with the output and ripple windings.
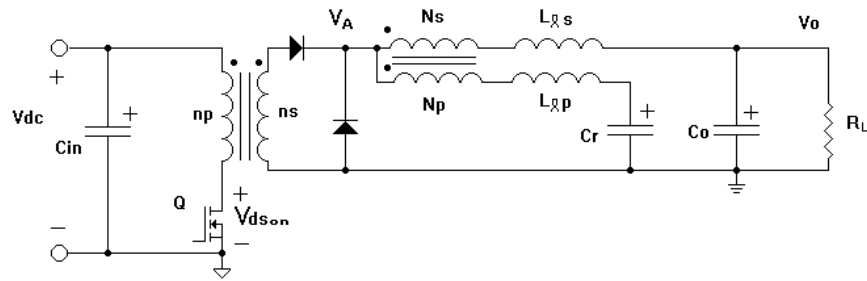
Fig. 1: Forward Converter with Output Ripple Steering

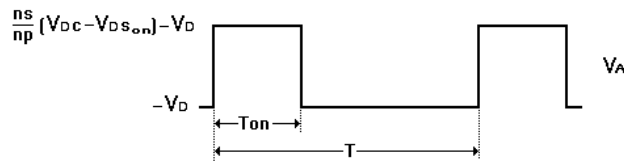The voltage waveform V_A as shown in Figure 2 feeds both the output and ripple windings.

Fig. 2

Figure 3 shows V_A driving both windings and NO LOAD, since R_L only determines the DC current. Also, windings N_S and N_P will be treated as an ideal transformer ratio with L_M representing the magnetizing inductance of the coupled inductor.
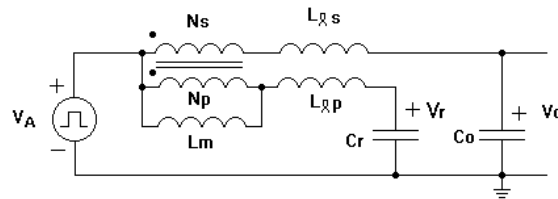

Fig. 3

where $$L_S = \left(\frac{N_S}{N_P}\right)^2 L_M$$

Since L_S and C_o form a low pass filter in which

$$f_c = \frac{1}{2\pi\sqrt{L_s C_o}} < f_s \qquad (Switching\ Frequency)$$

we have

$$V_O = \frac{T_{ON}}{T} V_A = DV_A$$

D is defined as the duty ratio $\quad D = \dfrac{Ton}{T}$.

It is also noted that L_M and C_r form a low pass filter in which

$$f_{cr} = \frac{1}{2\pi\sqrt{L_m C_r}} < f_s$$

Hence

$$V_r = \frac{Ton}{T} V_A = DV_A .$$

We note that Vo = Vr and are DC terms. Since we are interested in AC ripple terms, we can set the DC terms to zero (i.e., Vo = Vr = 0). This results in a simplified model shown in Figure 4.
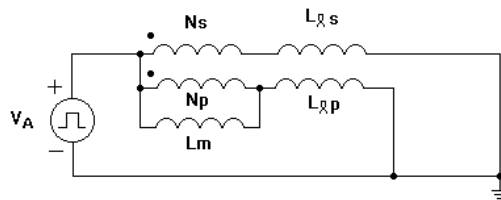
Fig. 4

We can redraw this circuit in a more understandable form (Figures 5-7).
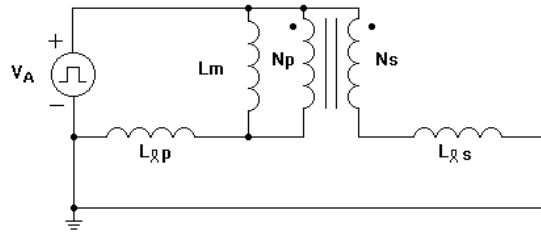
Fig. 5

Split the source voltage, V_A, into two identical sources as shown in Fig. 6.
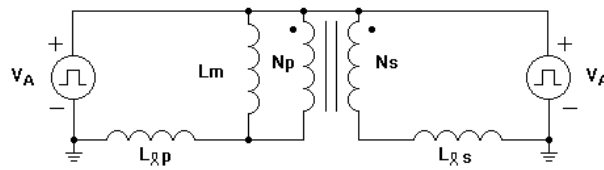
Fig. 6

Now, flip the circuit over to obtain a general form for the coupled inductor shown in Fig. 7.
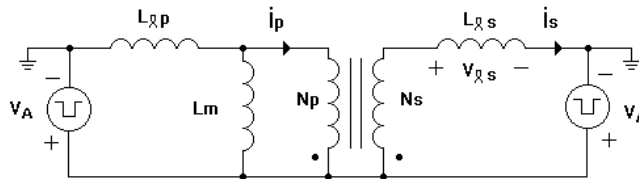
Fig. 7

Now that we have a simple form, we want the output ripple, i_s, to be zero (i_s=0). But from Faraday's Law:

$$V_{ls} = L_{ls} \frac{di_s}{dt}$$

The only way i_s=0 is if $V_{ls} = 0$. So, we must develop an equation with the constraint that $V_{ls} = 0$ which implies $i_s = 0$. Since $i_s = 0$, then $i_p = 0$ as shown in Figure 8.
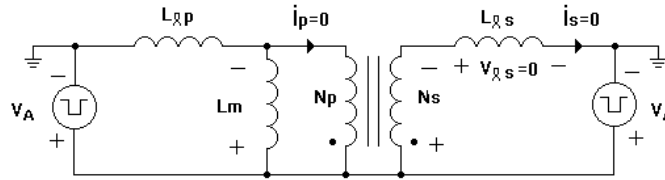
Fig. 8

For $V_{ls} = 0$ then $V_s = V_A$

But

$$V_S = V_M \frac{N_S}{N_P} = \frac{L_M}{L_M + L_{lp}} \cdot \frac{N_S}{N_P} \cdot V_A$$

Hence,

$$\frac{L_M}{L_M + L_{lp}} \cdot \frac{N_S}{N_P} \cdot V_A = V_A$$

Solving for L_{lp}:

$$L_{lp} = L_M \left[\frac{N_S}{N_P} - 1 \right]$$

Note: If $N_S/N_P = 1$, then $L_{lp} = 0$ which means that the leakage L_{lp} must be zero in order for the ripple, i_s, to be zero.

So, if we wind the ripple winding first (closest to the core) to minimize leakage L_{lp}, we can set the turns ratio to be 1:1, which makes it easy for mass production. Observe that the term

$$\frac{L_M}{L_M + L_{lp}}$$

steps the voltage V_A down, and to make V_s equal to V_A, the turns ratio N_S/N_P must step the voltage up by the same amount to obtain zero output ripple current.

Notice that L_{ls} is not in the equation for setting $i_s = 0$, but its value does play a crucial role. Since most things in life are not ideal, there will be voltage errors that will appear across L_{ls} which will produce a ripple current, i_s.

Voltage Errors:

1. The capacitors C_o and C_r will droop during T_{off} and rise during T_{on}; the rise and fall of the droop will not be the same, since $C_r \neq C_o$ and C_o aids in supplying the DC output current. This difference in slope appears as an error voltage, V_{erc}, across L_{ls},
where V_{erc} = Error due to capacitor slope difference.

2. An error due to the difference in voltage produced from the ESR of C_r and C_o and their associate ripple current.
Let V_{ERESR} = error due to ESR.

3. There is an error due to the turns ratio needed for zero ripple, since it is not practical to make

$$N_S \ / \ N_P \ = \ \frac{L_M + L_{lp}}{L_M}.$$

Let V_{ERN} = Turns ratio error

4. There is an inductive slope error. = V_{ERL}.
Since the square wave across the inductors will cause a tilt in the wave shape, the difference in tilt between the output and ripple winding will cause an error voltage.

These error voltages will cause a ripple current, i_s, to flow in the output in accordance with Faraday's Law:

$$\Sigma V_{errors} = \ L_{ls} \frac{d i_s}{d t}$$

Since the voltage errors are not in phase, they must be added using vectors.

Hence, the output ripple current is:

$$i_s \ = \ \frac{1}{L_{ls}} \int \Sigma \ V_{ERRORS} \ dt$$

From this equation, we want L_{ls} to be as large as possible to minimize the output ripple current, i_s. Note: If we added a small external inductor in series with L_{ls}, then the output ripple current due to the error voltages will be small.

Ripple current with external inductor added, shown in Figure 9.
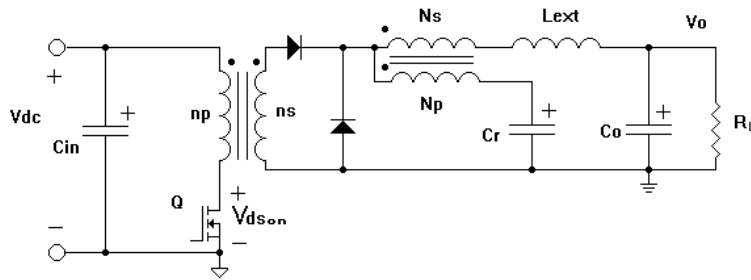
Fig. 9

$$i_s = \frac{1}{L_{ls} + L_{ext}} \int \Sigma V_{ERRORS} \, dt$$

Conclusion: When the basic principles of ripple steering were developed, it was shown that both leakages played an important role, and by adding an external inductor, the output ripple current caused by the error voltages can be significantly decreased.

Forward Converter
We now turn our attention to the forward converter with ripple steering on the input. In a basic forward converter, when the switch is on, current flows through the primary transformer winding. When the switch is off, there is no path for the current to go and, hence, it drops to zero. If we provide a ripple winding, then the current can flow through this ripple winding when the switch is off, as shown in Figure 10.
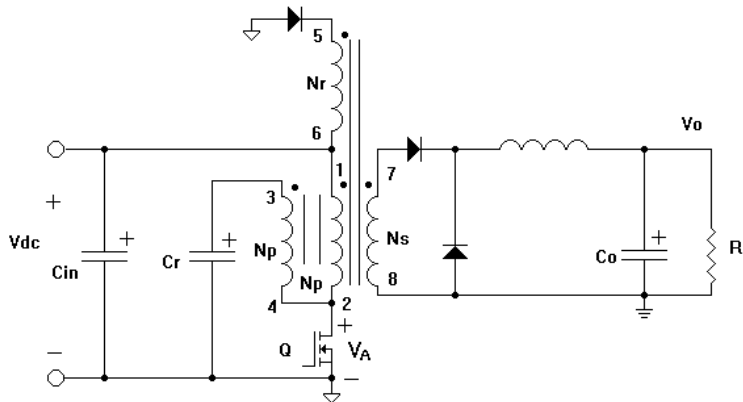
Fig. 10

We must first show that the voltage across C_r, V_{cr}, is equal to V_{DC}.

For the switch, Q, "ON", we have $V_{P12} = V_{DC} = V_{P34}$, since both windings have the same number of turns, N_P. Hence, $V_{cr} = V_{34} = V_{DC}$ during $0 \leq t \leq T_{on}$. Note: $V_A = 0$.

Now consider when the switch, Q, is "off", we have $V_{cr} = V_{DC} + V_{P12} - V_{P34}$

and employing KVL, we have

$$V_{cr} = V_{DC} \text{ during } T_{on} \le t \le T.$$

We conclude that

$$V_{cr} = V_{DC} \text{ for all } t.$$

Note:

$$V_A = V_{DC} + \frac{N_P}{N_r} V_{DC} = V_{DC}\left[1 + \frac{N_P}{N_r}\right] \qquad \text{During } T_{on} \le t \le T.$$

During Ton   During Toff
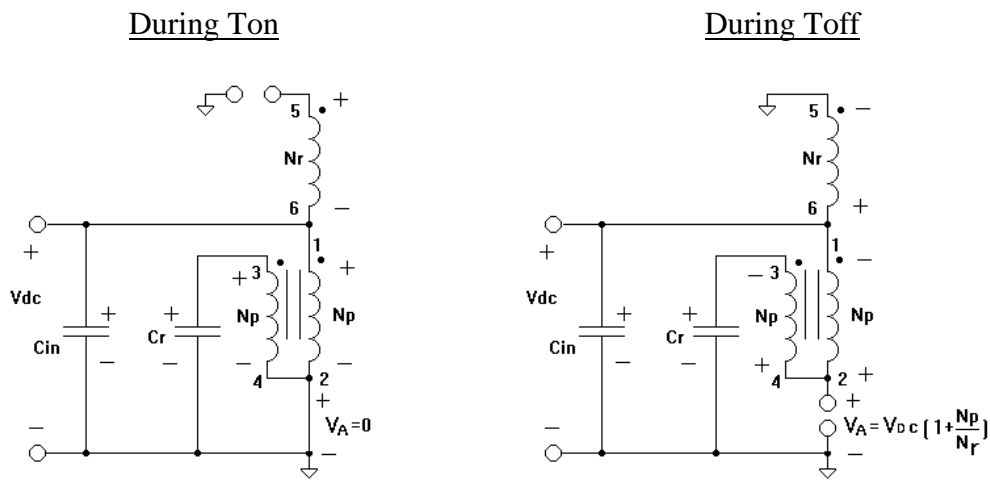
Fig. 11

Only the primary side in Figure 11 is shown, since we are presently only concerned about input ripple.

Since we are concerned about AC terms (ripple), then the DC terms can be shorted and the leakages of the windings and magnetizing inductance can now be added. Also, we treat the voltage V_A as a source, as shown in Figure 12.
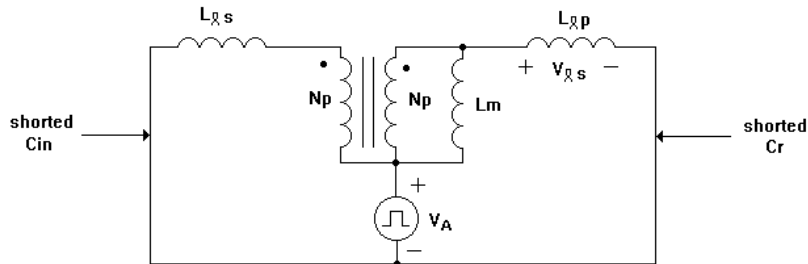
Fig. 12

The source voltage, V_A, can be split into two identical sources to obtain the basic model for ripple steering.
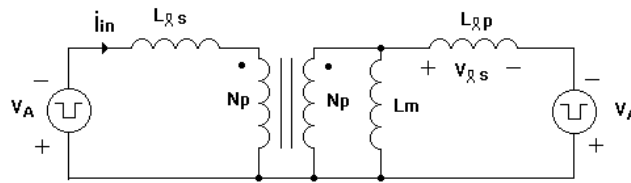
Fig. 13

Since the turns ratios are the same, then in order for i_{in} to equal zero, we must have $L_{lp}=0$, as in the previous example. Hence, we will wind the ripple steering winding first to minimize L_{lp}. We can now add an external inductance in series with L_{ls} to minimize the input ripple, i_{in}, due to the summations of the error voltages, as in Figure 14.
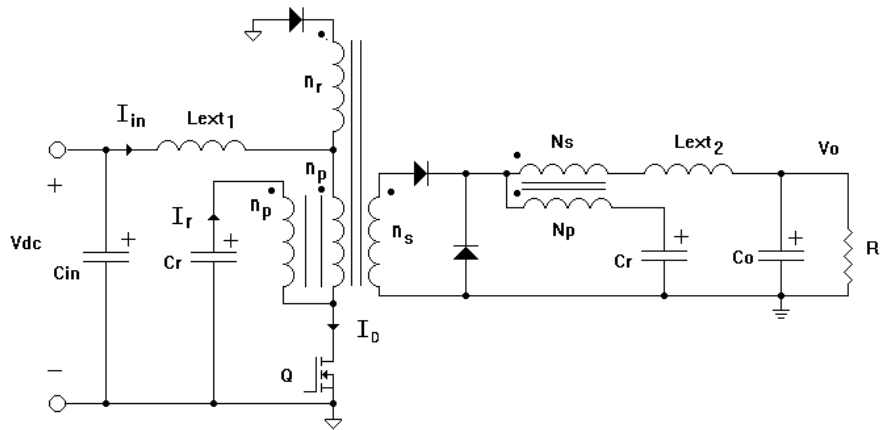
Fig. 14
Forward converter with non-pulsating input
current and ripple steering in both input and output.

Wave Forms
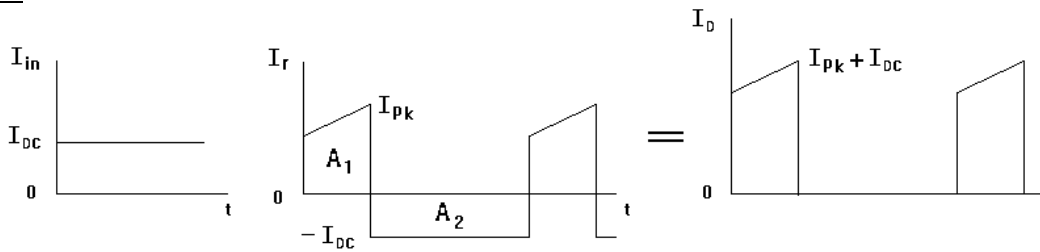
Fig. 15

NOTE: Amp-Sec A1 = Amp - Sec A2, since no net DC will flow through the capacitor, C_r.

Conclusion: A forward converter with non-pulsating input current has been derived based on the basic principle of ripple steering. It must be noted that the turns ratio between the primary winding, N_P, and the ripple winding must be 1:1. If the turns ratio is varied, there will be a large current flow during the turn off period.

Flyback with Non-Pulsating Input and Output Current

For non-pulsating input current, the same winding and capacitor technique used for the forward converter is employed, as shown in Figure 16.
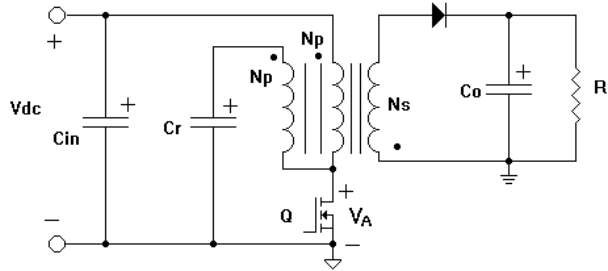
Fig. 16

The only difference between the two is that

$$V_A = V_{DC} + V_O N_P/N_S \text{ for the flyback and}$$

$$V_A = V_{DC} (1+N_P/N_r) \text{ for the forward converter. During } Ton \leq t \leq T.$$

Since the basic principle is the same for non-pulsating input current of a forward converter, it will not be derived for the flyback. The resulting schematic is shown in Figure 17.
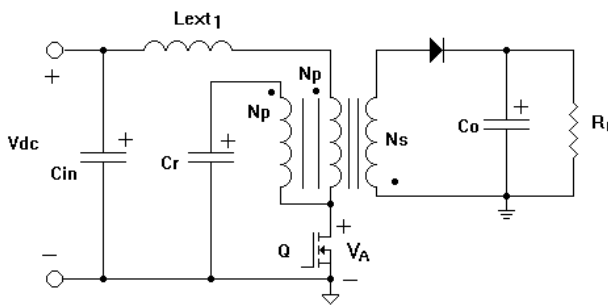
Fig. 17
Flyback with Non-Pulsating Input Current

As can be seen in Figure 17, the non-pulsating input flyback is identical to the non-pulsating input forward converter.

To obtain non-pulsating output current, a ripple steering winding is added to the output, as shown in Figure 18. The output section will be analyzed and put into the general ripple steering form.
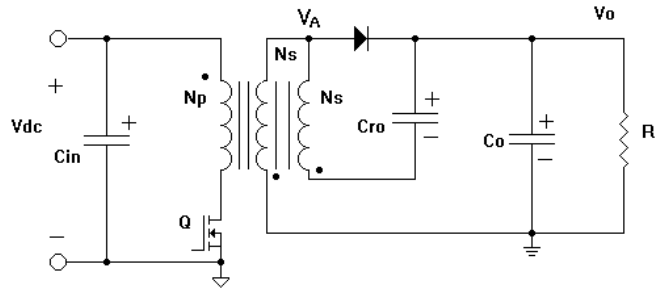
Fig. 18
Flyback with Non-Pulsating Output Current

The first step is to show that $V_{Cro} = V_O$. Consider the T_{ON} time and the T_{OFF} time of the switch, Q, as shown in Figure 19, for turn "on" and Figure 20 for turn "off".
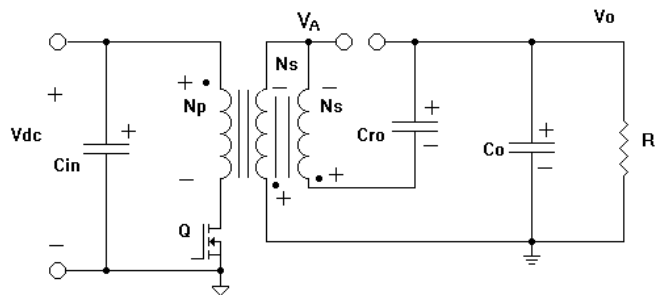
Fig. 19

Since the secondary turns and the ripple winding turns are equal, the voltage across their windings will be equal. Using KVL, we find $V_{Cro} = V_o$, with the polarity shown in Figure 19.

As shown in Figure 20, the voltage across C_{ro} during turn "off" is also V_o.

Hence, $V_{Cro} = V_o$ for all time, t.
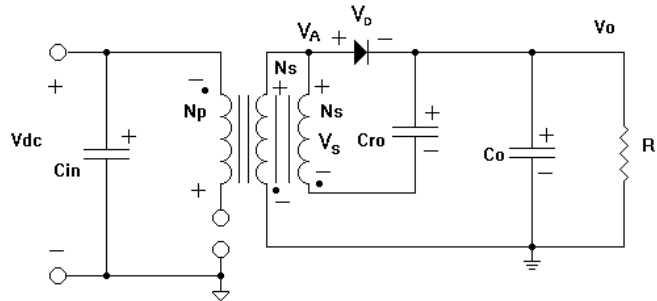
Fig. 20

Note that
$$V_A = -V_S = -\frac{N_S}{N_P}V_{DC} \quad \text{during Ton}$$

and
$$V_A = V_O + V_D \text{ during } T_{OFF} \ (Ton \le t \le T)$$

Also, since we are only concerned with the AC terms, we can set V_{Cro} and V_{Co} equal to zero to obtain Figure 21.

Output Section
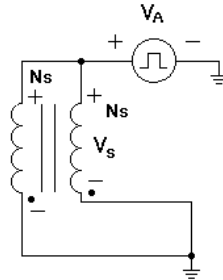
Fig. 21

Adding the leakages and magnetizing inductance, as shown in Figure 22, and splitting the voltage source V_A, we have the basic form for ripple steering, as shown in Figure 23.
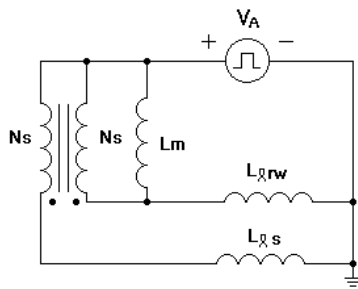
Fig. 22
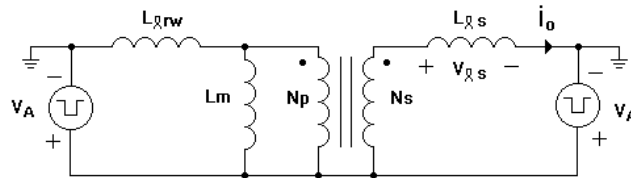
Fig. 23

Thus, to obtain $i_o = 0$, we must have $L_{lrw} = 0$, since the turns ratio is 1:1. Once again we can add an external inductor, $Lext_2$, in series with L_{ls} to minimize the ripple current io due to the error voltages. Figure 24 shows the flyback with the two ripple windings and external inductors.
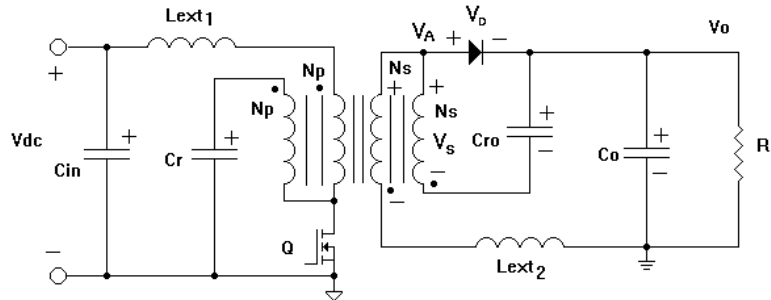
Fig. 24
Flyback Converter with both Non-Pulsating Input and Output Current.

Conclusion: It has been shown that by adding two ripple windings and two external inductors, the flyback converter will have non-pulsating input and output currents. In flyback converters, output ripple has always been a problem, leading to paralleling large bulky capacitors to minimize the fundamental ripple, as well as the large spikes due to the pulsating output current. By using ripple steering in the output, the current through C_o is very small, allowing the output ripple and capacitor's size to be very small.

Also, by adding ripple steering to the input winding, large pulsating currents will not be present in the input which minimizes the input capacitor, C_{in}, and significantly reduces the EMI problem associated with pulsating currents.

Input Filter
We can now turn our attention to the input filter and once again apply a ripple steering winding to reduce EMI due to the fundamental switching frequency and its harmonics. In Figure 25, we have a typical input filter connected to a power supply.
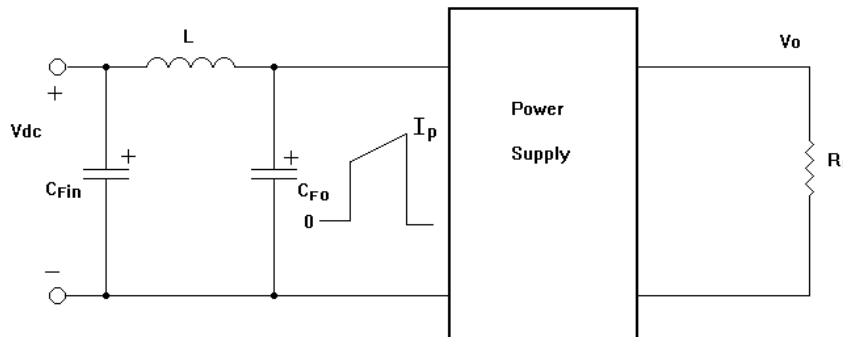
Fig. 25

The capacitor C_{Fo} typically sees a pulsed current, as shown in Figure 25. This pulsed current supplied partially by CFo will produce a voltage across the capacitor, which will be denoted as V_{signal} in Figure 26.
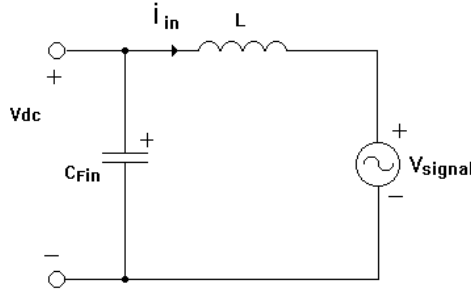
Fig. 26

The signal, V_{signal}, contains the fundamental frequency plus its harmonics. In Figure 27, a ripple winding is incorporated to minimize the ripple current i_{in} in order to meet EMI specifications.
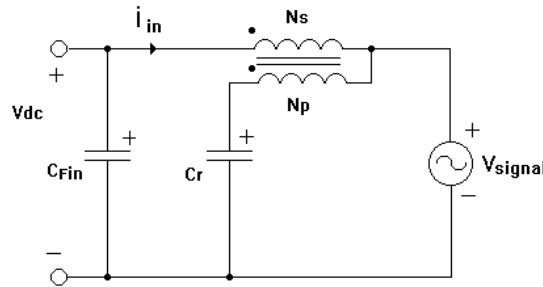
Fig. 27

As far as DC is concerned, the voltage V_{CFin} will equal V_{cr}, since we are dealing with a series circuit. Since only AC terms are considered, capacitors C_{Fin} and C_r can be shorted. Next, the magnetizing and leakage inductances are added. Also, the source, V_{signal}, is split, as in the previous samples, to produce the basic form for ripple steering, as shown in Figure 28.
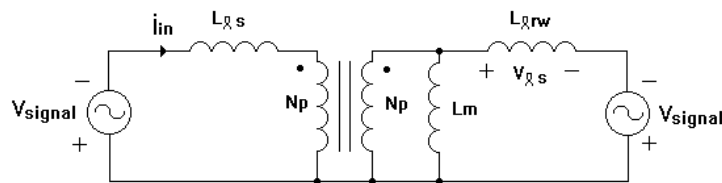
Fig. 28

In this case, N_S does not have to equal N_P, but it is still simpler for production to wind the ripple winding, N_P, first to minimize L_{lrw}, and set $N_S = N_P$. Then, by adding L_{ext}, the input ripple current, i_{in}, is minimized from the secondary effects of voltage errors.

The final filter is depicted in Figure 29.
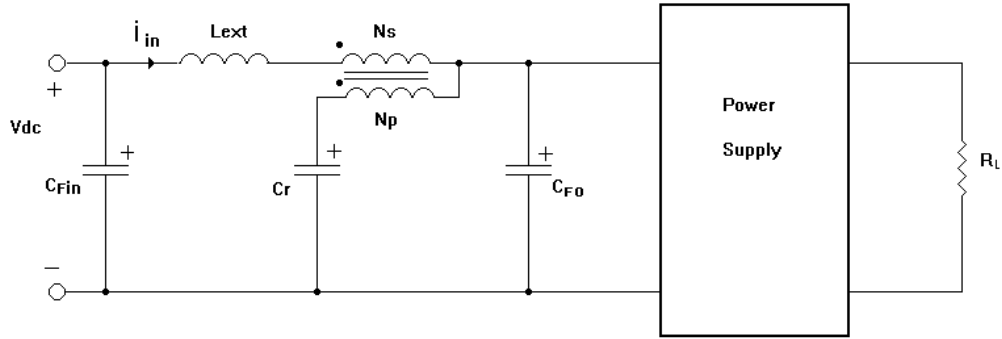
Fig. 29

Conclusion: Ripple steering windings have been applied to many different topologies, such as push-pull, Weinberg, boost, Barthold, etc., and performed as expected, which is to create non-pulsating input and output currents. Currently, the author is implementing ripple steering to solve common mode noise problems and three-phase ripple steering windings.

Ref: [1] Ripple current reduction circuit US patent #5038263 by J. Marrero and C. Peng.

IMPORTANT NOTICE