Designing An Environmentally-Friendly Ac to Dc Power Supply

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Across the world countries are demanding their ac-to-dc power supplies consume less power. The main component for these power supplies -- Green FPS (Fairchild Power Switch) as an example -- is a highly-integrated controller that combines the pulse width modulation (PWM) control, the MOSFET and a host of protection features into a tiny package. This article covers the steps needed to design an efficient power supply with these integrated controllers. It starts with specifying the requirements and then goes through the design considerations to realize an efficient, isolated, off-line, flyback switching-mode power supply (SMPS): the predominant, ac-to-dc power supply in use today. Starting with these requirements and assumptions, the factors governing the choice of magnetic components is explained. Then the criteria for selecting the Green FPS device are outlined and a low-loss resistor/capacitor/diode (RCD) snubber circuit is designed. The choice of rectifier diodes for the low voltage dc output circuits and the feedback circuit needed for regulating the dc outputs completes the design. The article concludes with some available resources to aid the ac-to-dc power supply designer.

All electronic gadgets derive their power from an ac supply. Some use chargers to store their power needs in batteries. More often than not, appliances are constantly plugged in but only do useful work when a consumer presses the power switch or a battery needs charging. Most of the latter constantly-connected devices consume considerable power even when no useful work is required of them. This fact has prompted a number of agencies throughout the world to tighten power requirements of these appliances to lower their idle standby power to below 1 W. Semiconductor companies have responded with high-functionality power switches that are used in efficient, off-line SMPSs to meet these new international requirements. Devices like the Green FPS have PWM control, an avalanche-rugged MOSFET and various protection and frequency modulation circuits built in with an advanced "burst-mode" circuit to achieve less than 1 W standby power. As a result of their higher level of integration, the design of these new isolated, off-line flyback SMPSs have become easier.

There are many topologies of ac-to-dc power converters and different modes of operation as well. For safety reasons, all power supplies need to be isolated. For these isolated supplies the usual choice is either the forward or the flyback topology. The latter uses fewer components and has the lowest cost, making it the power supply of choice. This article focuses on the flyback topology in realizing a low standby power, off-line, isolated, SMPS as shown in Fig. 1.

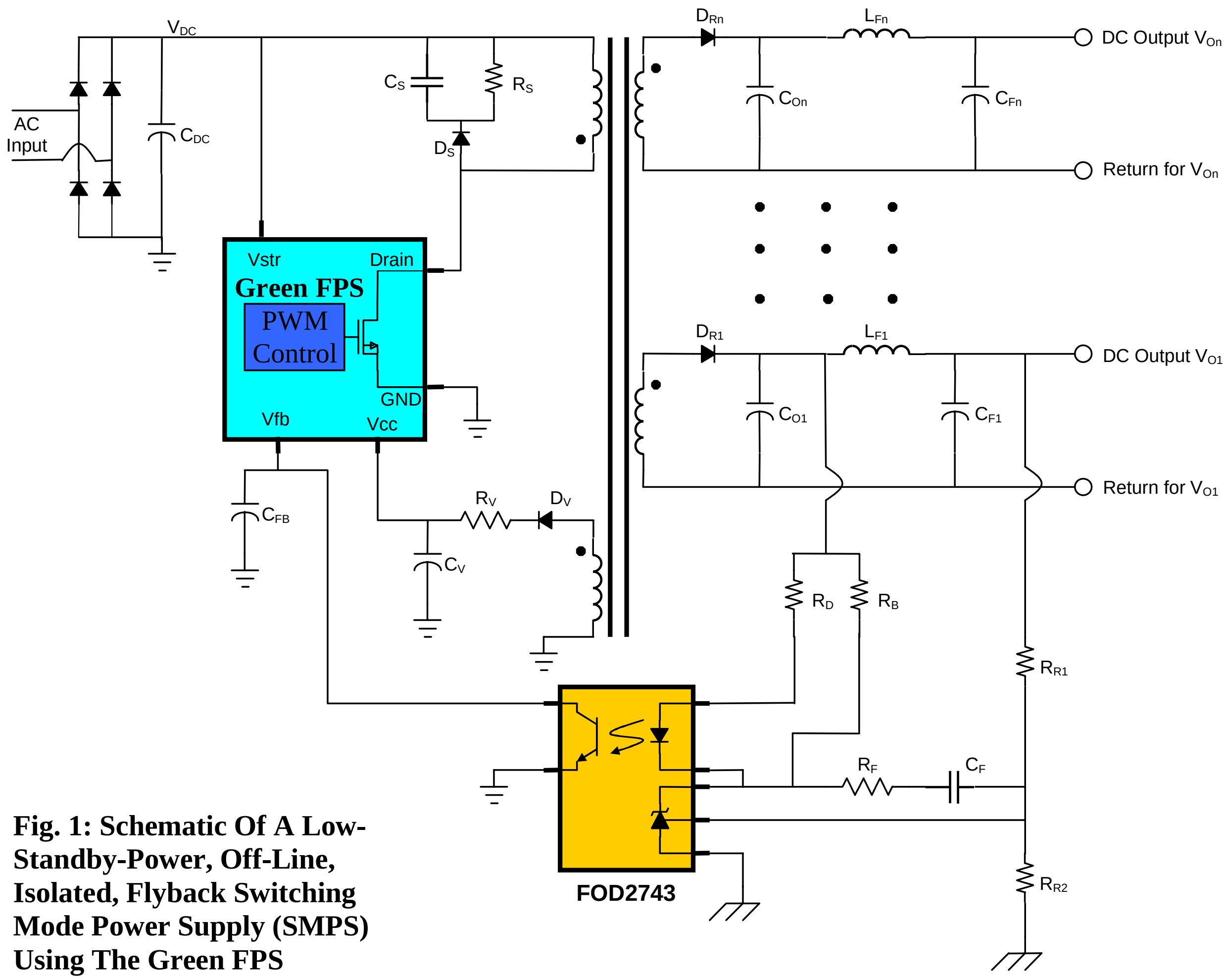

Fig. 1: Schematic Of A Low-Standby-Power, Off-Line, Isolated, Flyback Switching Mode Power Supply (SMPS) Using The Green FPS

The flyback topology stores energy in the transformer during the first part of the switching cycle when the power MOSFET (shown within the Green FPS device in Fig. 1) is on and current flows through the primary windings of the transformer, and releases it through the secondary windings during the second part of the switching cycle when the MOSFET is off. If all the energy in the transformer is dissipated before the start of the next switching cycle, the mode of operation is known as discontinuous current mode (DCM). If this DCM condition is not met, then the SMPS is said to be operating in the continuous current mode (CCM). DCM operation is suitable for high-voltage and low-current SMPS designs while CCM is suitable for low-voltage and high-current designs. Another mode of operation is voltage mode versus current mode. In voltage mode only a voltage-feedback loop is used to make sure the SMPS regulates the output voltage; whereas in current mode, both the voltage-feedback loop and an internal current-feedback loop are used where the current loop limits the current flowing through the power MOSFET (done completely within the Green FPS device) on a switching pulse-by-pulse basis. Needless to say current mode is preferred and most Green FPS devices are designed to operate in this mode.

This article focuses on current mode of operation and where the SMPS is operating at the boundary between CCM and DCM at the condition of minimum ac input voltage and maximum load current on all low voltage dc outputs. Thus, for input voltages higher than the minimum and/or for output current loads less than the maximum, the SMPS will operate in DCM.

There are three major steps in realizing this SMPS so as to make the design process easy and yet realize a tiny and efficient power supply. They are:

- Determine the input, output and other design requirements
- Select the Green FPS device and the flyback transformer needed
- Design the low-voltage dc output circuitry with regulation via a feedback loop

The first step is to determine the input ac voltage, input line frequency, low-voltage dc output voltages and the maximum current loads for each dc output. Using these general requirements a calculation of input power is made assuming 80% efficiency for an SMPS with a small number of higher voltage (12 V and above) outputs and 70% efficiency for an SMPS with many lower voltage outputs. The ac input voltage is typically the universal voltage range of 85 V to 265 V to cover the extreme voltages of both the 110 V and 230 V standards worldwide. Some systems such as STBs for European television may need to be designed only to the 230 V ±15% standard while STBs in the US may require only 110 V operation. However, most off-line power supplies are designed for the universal input voltage range so this article focus only on this input voltage range.

The corresponding input line frequency range is from 47 Hz to 63 Hz. The dc input capacitor (CDC in Fig. 1) is chosen based on a capacitance of about 2 - 3 µF/W of input power. The voltage across this capacitor, called the dc input voltage and symbolized as V_{DC}, settles at near the peak of the ac input voltage. The output dc voltages and maximum currents are based on the system requirements where it is typical to create multiple voltages of 5 V and higher, and then use these voltages with subsequent point-of-load, dc-dc converters to generate lower voltages of between 0.9 V and 3.6 V.

The second step is to select the Green FPS device and the flyback transformer needed. The choices of the flyback transformer and the Green FPS are interwoven together. A typical assumption made here is that the maximum MOSFET "ON" duty cycle is set between 45% and 50% to minimize the possibility of sub-harmonic oscillation -- for duty cycles higher than 50% and when the off-line converter is operating in the CCM. A lower duty cycle, on the other hand, while reducing the voltage stress on the power MOSFET, does cause higher voltage stresses on the output dc diodes (D_{R1} … D_{Rn} in figure 1). Since the power MOSFET within the Green FPS is usually rated for voltages between 650 V and 800 V, a higher duty cycle near 50% can be tolerated.

The first stage is to calculate the primary side inductance of the flyback transformer at the maximum output load and minimum input voltage condition by assuming a certain switching frequency for the Green FPS device. This primary inductance is also dependent on the minimum input dc voltage (V_{DC}), the maximum duty cycle chosen above and the input power calculated above. The peak current through the MOSFET can be calculated since it is dependent on the maximum duty cycle, input power, minimum input dc voltage, the primary side inductance and the switching frequency. With this peak value of current and the switching frequency needed, the Green FPS device can be chosen from the current list in the table below. It is typical to allow for about a 10% margin from the worst case specifications.

Green FPS Product Number	Maximum MOSFET Drain Voltage (V)	Peak MOSFET Drain Current (A)	Typical Switching Frequency (kHz)
FSD200	700	0.3	134
FSD210	700	0.3	134
FSDM311	650	0.55	67
FSDH321	650	0.7	100
FSDL321	650	0.7	50
FSD1000	700	adjustable	67
FSDL0165RN	650	1.2	50
FSDH0265RN	650	1.5	100
FSDM0265RN	650	1.5	67
FSDM0365RN	650	2.15	67
FSDL0365RN	650	2.15	50
FSDM0565RB	650	2.3	67
FSDM07652RB	650	2.5	67

Table 1: Green FPS Devices And Salient Specifications

The choice of transformer cores is an entire subject by itself. A rough choice can be made using Table 2 which allows a quick selection of cores for a typical 67 kHz switching frequency and a single dc output based on the output power of the off-line converter. For higher switching frequencies, a smaller core can be used while for multiple dc outputs, a larger core is required.

Output Power (W)	EI core	EE core	EPC core	EER core
0 – 10	EI12.5 EI16 EI19	EE8 EE10 EE13 EE16	EPC10 EPC13 EPC17	
10 – 20	EI22	EE19	EPC19	
20 – 30	EI25	EE22	EPC25	EER25.5
30 – 50	EI28 EI30	EE25	EPC30	EER28
50 – 70	EI35	EE30		EER28L
70 – 100	EI40	EE35		EER35

Table 2: Quick Core Selection Table For Single Output And 67 kHz Switching

While this approach is simplistic, the initial design of the off-line converter can be made and checked against other constraints that may force the need for a larger core. With the core chosen the number of turns for both the primary side and secondary windings of the transformer are calculated based on the output voltages required, an estimate of the output diode forward voltage drops and the minimum number of primary turns required to prevent core saturation. For all products in Table 1, except the FSD200, a bias supply voltage is needed and the number of turns is calculated for this supply voltage at this time. (The FSD200 creates its own supply voltage directly from the input dc voltage which saves board space and components at the expense of lower efficiency.) The wire thickness can be determined based on the maximum current density which is usually between 5 A/mm² to 10 A/mm². All windings on the corresponding bobbin of the chosen core are examined along with the allowances for insulation tape thickness for safety (creepage) between primary and secondary windings, to determine if all the windings fit within the allowable window based on the core specifications. Accordingly a new core may be chosen and the steps after the core choice (above) may need to be repeated to achieve a workable design.

Because flyback transformers store energy during the MOSFET "ON" cycle without releasing this energy until the MOSFET "OFF" cycle, a gap is needed in the core to prevent saturation. The center leg gap can be calculated from the specifications of the core chosen, the number of primary turns and the primary inductance needed. Core manufacturers provide cores with and without gaps in the center leg of the EE, EI, EPC and EER cores mentioned in Table 2. Core loss estimates need to be looked at when choosing the particular ferrite material of the core based on the chosen switching frequency.

Every flyback transformer has primary winding leakage inductance (determined by measuring the primary inductance when all the secondary windings are shorted) that cause high-voltage spikes on the MOSFET drain. To prevent destroying the MOSFET, a couple of "snubber network" solutions are often employed. The one used in Fig. 1 (network consisting of R_S, C_S and D_S) is called the RCD snubber (resistor-capacitor-diode) but the resistor and capacitor can be replaced with a Transient Voltage Suppressor (TVS, which is similar to a fast-transient-response Zener diode) with a breakdown voltage that protects the MOSFET (eg the P6KE150A from Fairchild Semiconductor). With the RCD snubber shown in Fig. 1 the voltage at the common junction between the diode (D_S) and the resistor/capacitor (R_S/C_S) is designed to stay essentially constant. During the MOSFET "OFF" cycle the diode forward biases and delivers charge to the capacitor, clamping off the peak drain voltage of the MOSFET. The resistor (R_S) discharges the capacitor (C_S) to return the energy back to the dc link capacitor C_{DC}, thus minimizing the loss from this snubber network.

The third and final step is to design the low-voltage dc output circuitry with a regulation feedback loop. The rectifier diodes (D_{R1} ... D_{Rn} shown in Fig. 1) are selected on the calculated values of maximum reverse voltage and the forward rms current through each diode, based on a number of the calculated and estimated values above. With the diodes chosen, the forward voltages can be checked against the estimates made when the number of turns for the secondary windings were being calculated. Fig. 1 shows an output capacitor (C_{O1}) followed by an inductor-capacitor (LC) filter stage, made up with L_{F1} and C_{F1}. If the voltage ripple requirements of the dc outputs can be met with a single capacitor then the LC filter can be removed, which will save space and cost. There may be other transient load, or stringent load, regulation requirements that may affect the design of this output stage which need to be factored in too.

To regulate the low voltage outputs, a feedback signal needs to be sent to the Green FPS device which controls the pulse width based on the output dc voltage. This signal needs to pass through an isolation optocoupler to satisfy the safety requirements for this isolated flyback converter. A simple way of doing this is to use a voltage shunt regulator and an optocoupler integrated into a single device (eg the FOD2743 from Fairchild Semiconductor) as shown in Fig. 1. The reference dc output voltage is dropped down to the reference specification voltage of the shunt regulator

(2.5 V for the FOD2743) via a resistor divider network (R_{R1} and R_{R3}) and R_B is inserted so as to maintain the minimum current requirements of the shunt regulator. The current through the photo-transistor within the FOD2743, resulting from the current through the LED, needs to be balanced against the current sourced by the feedback pin of the Green FPS device so as to keep the feedback voltage within its required range. During standby, when little to no output load current is consumed, the feedback voltage falls to a low threshold value to trigger "advanced burst mode" operation where the Green FPS device switches in bursts to restore the outputs to their desired voltage. Depending on the ratio of standby power consumed to operating power, this "green," environmentally-friendly mode will save considerable power by eliminating many switching cycles internal to the Green FPS device. Compensation of the feedback loop is achieved via selection of values for R_F and C_F. For the LC filter output stage (L_{F1} and C_{F1} for the reference output), the 3 dB point of the LC filter needs to be high enough not to interfere with this feedback compensation loop.

Final housekeeping is to pick a supply voltage capacitor, C_V and the diode D_V (see Fig. 1). The amount of capacitance required is based on the amount of supply current needed by the Green FPS device chosen. A small resistor, R_V, is inserted so as to remove the sensitivity of this supply voltage to load variations of the other outputs. All the other circuitry, such as soft start, leading edge blanking, overvoltage, overcurrent, overload and thermal shutdown protections are all incorporated within the Green FPS device without any need for external circuitry. There are many design tools that help with all the calculations required to realize such off-line converters; an example of such a tool is found in reference [2].

There are other things that go into off-line converters such as the input EMI filters, internal EMI filtering, construction of transformers to minimize leakage, maximize efficiency, minimize bulky EMI components through shielding or handle acoustic problems, and a host of other issues that crop up for power supply designers who design off-line converters regularly. However, for power supply designers wanting to embark on these designs for the first time, the steps above along with a canned solution of an input EMI filter will allow them to get a good, first-pass design of an off-line converter.

A walk through the design of an off-line isolated flyback SMPS using Green FPS has been described. These ac-to-dc power supplies are used where standby power needs to be reduced to below 1 W to comply with various regulations throughout the world. The design has been broken into three steps, namely: specifying the requirements of the off-line power converter, choosing the flyback transformer and IC components needed and, lastly, designing the low voltage dc output circuitry and the corresponding feedback loop needed for regulation. The design with these integrated Green FPS devices, allow a much simpler and more robust design to be made by designers who may be new to SMPS designs.

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