**ur Notebook continues with the second and final part of Switched Power Supplies**

SWITCHING POWER supplies can use capacitive elements as the energy transfer medium, rather than magnetic components which have been considered so far. Generally, capacitive circuits are limited to use at high frequency (greater than 10 kHz) and relatively lower power levels. Figure 4 shows a capacitive voltage multiplier and a voltage inverting circuit. An example of such a circuit, which is available in integrated form, is the ICL7660 from Intersil Inc.

Operation of the circuit in Figure 4a is as follows. initially, SW2 is closed and SW1 'off'. Capacitor C1 is charged to $V_{IN}$ through rectifier D2 and SW2. SW2 then opens and SW 1 is closed. This causes the voltage seen at the anode of rectifier D1 to rise from $V_{IN}$ to a value determined by the relative sizes of capacitors C1, C2. When C1 = C2, the voltage at the output of the supply will rise toward $2V_{IN}$. SW1 is then opened and SW2 closed to repeat the cycle.

The circuit in Figure 4b operates on the same principle. SW1 charges capacitor C1 to $V_{IN}$. SW2 is then closed taking the cathode of rectifier D1 negative to a value determined by C1, C2. Capacitor C1 is then recharged through SW 1 and D2.

## What Semiconductor?

As is inferred by the name 'switching mode' the semiconductor devices required for this application are primarily switching devices. The requirements for the switches are:

- Low conduction losses.
- Fast switching times.
- Voltage rating to match the circuit configuration and input supply voltage.
- Ability to withstand an overload.
- Good safe operating area (SOA) when used in an inductive load switching circuit.

These requirements can be met largely by a wide variety of bipolar transistors, thyristors and SCRs. More recently, power MOSFETS have been introduced with voltage and current rating! suitable for use in switching power supplies (Current ratings to 40A and voltage ratings to 500 V). These devices offer substantial advantages over bipolar transistors in the following areas:



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- Low gate drive power — simplifying the driver stage.
- Fast switching times which are largely temperature insensitive — allowing operation at frequencies greater than 50 kHz.
- Good overload capability — the device is not limited by gain or second breakdown. Power dissipation is the limiting factor.
- The positive temperature coefficient of 'on' resistance assists current sharing when devices are parallel-connected to achieve higher current ratings.

Rectifiers for switching power supplies have similar requirements to the switching devices. The type of rectifier used is governed by the circuit application as indicated in Table 1.

Monolithic switching regulator circuits of limited output power capability are available (Fairchild uA78S40, Texas TL497A), and the trend toward integrated power functions can be expected to accelerate. There are a number of integrated control circuits for switching mode power supplies available, allowing the control circuit board complexity to be reduced. The functions available in these circuits include: an oscillator, a voltage reference, a regulator, a current limit function, and a driver stage. Some of the more common devices are: Philips TDA1060 which is pin-for-pin compatible with the Signetics NE5560; the Silicon General SG3524 which is multi-sourced; the Texas Instruments TL494 which is also available from Motorola; Fairchild and Fujitsu (as MB3759); and the Motorola MC3420.

## Magnetic Component Design

Magnetic components are used in the majority of switching mode power supplies. It is, generally, only at low power and high frequency that capacitive circuits can be used. Magnetic components are used not only as high frequency transformers and DC inductors, but also as drive transformers, providing isolation between the control circuit and the power switching elements, and as current sensing elements.

Some of the criteria for the selection of a magnetic component as a high frequency transformer core are:

- Operating frequency range.
- Maximum magnetic flux density.
- Loss coefficient at the operating frequency.
- Available winding area.
- Primary to secondary coupling factor, and isolation.

Ferrite cores in a variety of shapes and materials are available. Metal power cores, laminated and tape wound cores are also available for specialist applications.

## Transformer Design

As an example, consider the design of a switching mode transformer to operate at 50 kHz in a half bridge circuit (refer to Fig. 3d). The input voltage is 310 V + 5%, - 10% and the output required is 5 V at 40 A.

**Step 1.** Select a core material suitable for operation at 50 kHz and a core size commensurate with the power loading. Example: Mullard FX3740 core, A16 material; Philips EC52/24/14 core, 3C8 material.

**Step** 2. Calculate the number of primary turns required to avoid saturation of the transformer core under worst case loading. Check that the worst case core losses do not cause excessive core operating temperature. Check that the winding area is adequate. Check that the magnetizing current is less than 10% of the load current for efficient operation. Example: Worst case loading will occur with maximum input supply voltage and maximum duty cycle for the switches.

$$\frac{V_{IN}\max\ \delta\max}{f_o} = \hat{B}.\ Ae.\ n$$



where $V_{IN}$**max** is the maximum voltage applied to the transformer = (310 + 5% V)/2
$F_0$ is the operating frequency = 50 kHz
B is the peak working flux density of the core, at elevated temperature = 200mT
Ae is the magnetic cross-sectional area of the core = 180 mm²
n is the minimum required number of turns
Hence $n_{min}$ = 40.7 turns

Working at a peak flux of 200 mT, at 50 kHz, core losses are approximately lW8. This corresponds to a rise in core temperature above ambient of approximately 20°C. Assuming a conversion efficiency of 70%, the input power requirement is 286 W. The lowest input voltage, applied across the transformer primary is (310-10%)/2V = 139 V. This gives a primary winding current, assuming 0.9 duty cycle, of approximately 2A3.

Assuming a current density in the transformer winding of 4 **A/mm²,** the cross-sectional area of wire used for the primary winding should be 0.57 mm*, corresponding to a wire of diameter 0.85 mm. Assuming a packing factor of two (because a circular cross-section conductor is used) the winding area consumed by the primary winding will be 2n x 0.57 **mm²** = 46.7 **mm².** The available winding area on the core, after making an allowance for isolation is 304 **mm².** The primary winding will take only 1/6th of the available area.

**TABLE 1**

| Application | Rectifier Type |
|---|---|
| High Frequency Switching | Schottky<br>Epitaxial<br>Fast recovery, diffused |
| High Current, Low Voltage Switching | Schottky<br>Epitaxial<br>Germanium |
| High Voltage Switching | Silicon diffused Rectifier stack |

The magnetizing inductance of the winding is determined by:

$$L_m = \frac{\mu_o\,\mu_a\,n^2\,Ae}{l_e}$$

where $L_m$ is the magnetizing inductance in Henries
$u_{\_}$ is the permeability of free space = 4 x $10^{-7}$ H/m
$u_a$ is the amplitude permeability of the core = $10^3$
$l_e$ is the magnetic path length in the core = 105 mm

$$L_m = 3.62\ \text{mH}$$

The peak magnetizing current is given by the equation:

$$\frac{V_{in}\min}{2} = \frac{2.L_m\,I_i\,f_o}{\delta\max}$$

So

$$I_m = \frac{V_{in}\min\ .\ \delta\max}{4.\ L_m.f_o} = 86\ \text{mA}$$

The peak magnetizing current represents 4% of the load current, which is acceptable.

**Step** 3. Establish the transformer turns ratio. Example: The voltage required at

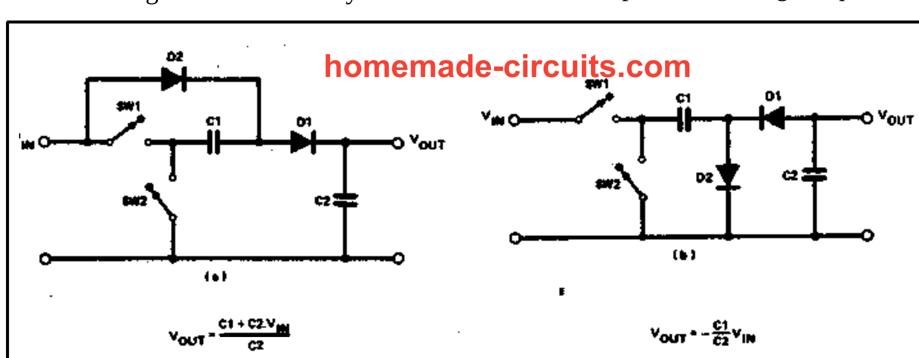




**Fig. 4. Capacitive converter circuits. (a) Cnpadtive voltage multiplier. (b) Capacitive voltage ioverter.**

the secondary winding of the transformer is a function of the power supply output voltage (5 V), the duty cycle of the switches SW1 , SW2, and the voltage dropped across the rectifiers and resistance of the output inductor L1 , Disregarding the circuit losses initially, the transformer output voltage can be found by balancing the volt-second products for the output inductor in the minimum input supply condition, when the duty cycle is 0.9.

$$(V_x - V_O) = (V_O + V_F)(1 - \delta)$$

where $V_x$ is the transformer output voltage.
$V_O$ is the supply output voltage =5v
is the duty cycle =0.9
$V_F$ is the rectifier forward drop =1V

$V_x$ = 5V7



To this figure must be added the circuit losses, $V_F + I_o.R_L$, where I, is the rated output current, and $R_L$ is the series resistance of L1 and the circuit wiring.

A minimum output voltage of 7 V can be used. The minimum input voltage 'is 139 V, so the transformer turns ratio is 20: 1. Assuming a primary winding of 40 turns (marginally below the minimum, resulting in a slightly higher peak flux density, B, which can be tolerated in this example), each secondary winding comprises two turns.

**Step** 4. Transformer winding design. The correct design of the transformer windings will result in a reproducible and efficient transformer design. The conductor size and placement can have a significant effect on winding losses in a high frequency design. Example: The primary winding consists of 40 turns of 0.85 mm diameter wire, which can be wound in two layers each comprising 20 turns. The available winding breadth on the transformer core is approximately 20 mm after an allowance of 4 mm at either end for isolation. The secondary consists of two windings, each of two turns. The conductor for these windings is in strip form, being 8 mm in width and 0.625 mm thick. The windings are wound side by side on the former. Electrostatic screens and isolation are wound between primary and secondary windings. Worst case windings losses arise at maximum loading. Primary winding loss is 3W4 maximum, and the secondary winding loss 1W25 watts maximum. When added to the transformer core losses of 1 W8, the worst case transformer loss is 6W45 at a core temperature of 100°C. The transformer is capable of operating in ambient temperatures up to 35 °C without additional heatsinking. (Core data and ratings are drawn from the manufacturer's literature).

## Inductor Design

The operating conditions of the magnetic core in the inductor are significantly different from those of the switching mode transformer. The core must withstand a DC magnetizing field, without saturation. For this reason, an air gap is commonly introduced into a magnetic circuit. This can be either in the form of a single gap introduced, say, in the centre pole of an 'E' core, or can be a distributed gap throughout the core material. The distributed gap solution presents a lower radiated magnetic field. When a gapped core is used, the magnetic flux is sorted mainly in the gap. There are small flux excursions as the load current ramps up and down. As an example, consider the design of an output filter inductor to be used with the 50 kHz transformer previously designed. The operating frequency will be 100 kHz. The maximum output current is 40 A and the minimum output current for continuous current flow in the inductor is 4A.

**Step 1.** Calculate inductance value required, and the energy storage capability required. Example: The minimum voltage applied to the inductor by the transformer secondary winding is 5V7 with a 0.9 duty cycle. The current in the inductor can be allowed to rise by 8 A maximum during this time, if the current flow is to remain continuous when the output loading is minimum, i.e. 4A.

$$(V_{IN}\ min - V_O) = L\ min. \frac{I_L . fo}{\delta\ max}$$

where $V_{IN}$**min** is the voltage applied to the inductor = 5V7
$V_o$ is the output supply voltage = 5V
Lmin is the minimum inductance value
$I_L$ is the peak to peak inductor current =8A
fo is the operating frequency = 100 kHz
max is the switch duty cycle =0.9

lmin = 1.6 microhenries

The energy storage capability is $L.I_m^2$ where I,,, is the peak current flowing in the inductor = 44 A, so $L.I_m^2$ = 3.1 mJ.

**Step** 2. Select a suitable inductor core and determine the air gap required (if it is not a distributed gap material). The majority of magnetic core manufacturers provide selection charts/guides for this purpose. Example: Philips core EC35/17/10 with a 0.9 mm air gap will meet the energy storage requirement (equivalent to the Mullard FX3720).

**Step** 3. Calculate the number of turns required and determine the inductor losses. The core data gives an effective permeability or an $A_L$ value (inductance per turn of the coil) for gapped cores, which enables the number of turns to be calculated and rounded up to the nearest half turn. The inductor losses are primarily in the winding and these can be determined using a similar method to that used to calculate the transformer winding losses. Example: For the Philips EC35/17/10 core with a minimum air gap of 0.9 mm, 4 turns are required to give an inductance of 1.6 microhenries. The winding losses can be written as $I_{eff}^2.F_R.R_{DC}$ where:
$I_{eff}$ is the RMS current flowing in the inductor winding.
$F_R$ is a resistance multiplier to account for high frequency operation.
$R_{DC}$ is the DC resistance of the winding.

The high frequency impedance of the winding is a minimum for a conductor of thickness 0.57 mm. Making the winding with copper strip of thickness 0.5 mm and width 20 mm gives a 100°C AC winding resistance of 0.58 mR. The winding loss is OW93, resulting in an inductor temperature rise above ambient of 18 °C when fully loaded.

## Drive Transformer Design

Various approaches to the design can be made, though the choice is frequently restricted by the operating conditions and the drive requirements of the semiconductor switch. Thyristors and power MOSFETS can be driven by pulse transformers. The length of the trigger pulse and the circuit impedance are designed to comprehend the drive requirements of the worst case drive. Bipolar transistors require a continuous base current supply which often results in a larger transformer core being needed. The need for a wide variation in switch duty cycle often results in the drive supplied to the switching device being compromised; the forward base current supplied during long duty-cycle opeation may be the bare minimum to maintain the transistor in saturation. At short duty-cycles, the base current supplied can be far in excess of the device requirements, compromising its switching performance. This effect is less severe when power MOSFETS are used as the switches, since they do no exhibit storage time effects.

As an example, consider the design of drive transformers for power MOSFETS when used as the switches in the 50 kHz switching mode power supply. A single transformer with two primary and two isolated secondary windings could be used. A disadvantage of this approach, however, is the absence of negative gate bias to turn off the MOSFETS at any duty cycle other than the maximum of 0.5, which would give poor noise immunity in normal operation. Instead, separate transformers are used and the magnetizing energy stored in the transformer core during the conduction phases is used to assist turn-off. The transformer design is similar to' that required for a single-ended forward converter (Fig. 3b).

**Step 1. Select a** suitable magnetic material and core size. Example: The operating requency is 50 kHz and the average current flow in the windings will be low. A core material with a high permeability is desirable to maintain a low level of magnetizing current. Winding area is a significant factor in determining the core size and will depend on the isolation voltage rating desired. For this application consider the Philips core P1418 in 3B7 material, with an $A_L$ value of 2,200 mH/lOOO turns and a total winding area of **9.4 mm².**

**Step** 2. Calculate the number of turns required for the primary winding and the magnetizing inductance and current. Example: To avoid core saturation when operating at maximum duty cycle, with a supply voltage of 15 V, the minimum number of turns required in the primary winding is given by:

$$\frac{V_{in}\cdot\delta\,max}{f_o} = \hat{B}\cdot Ae\cdot n_{min}$$

where $V_{IN}$ is the supply voltage = 15v
$\delta$ max is the maximum duty cycle = 0.45
$f_o$ is the operating frequency = 50 kHz
$\hat{B}$ is the peak magnetic flux density in the core = 180mT
Ae is the magnetic cross sectional area of **the** core = 25.1 mm’
$n_{min}$ is the minimum number of primary turns 
Hence $n_{min}$ = 30 turns

The magnetizing inductance, with n, the number of turns equal to $n_{min}$ is given by:

$$n_{min} = 10^3\sqrt{\frac{L_M}{A}}$$

where:
$L_M$ is the magnetizing inductance in millihenries
$A_L$ is the inductance factor in nanohenries/lOOO turns = 2,200
Hence $L_m$ = 2.0 **mH**

The magnetizing current at maximum duty cycle is:

$$I_M = \frac{V_{IN}\cdot\delta\ max}{L_M\,fo} = 67.5\ mA$$

**Step** 3. Check that the winding area on the ferrite core is adequate. Example: To calculate the winding area required for the primary winding, we must first estimate the average current flow. The current required to drive the power MOSFET IRF720, which would be used in this application, at 50 kHz, is low compared to the magnetizing current (1.7 mA averaged over a switching cycle). So, the average magnetizing current level can be assumed. A suitable wire gauge is 0.1 mm diameter. Because of handling difficulties, a 0.2 mm wire may be preferred. The winding area consumed is approximately 20% of the total winding area of the transformer. Assuming that the drive transformer has a 1:l turns ratio, giving a ±15 V gate drive to the power MOSFET, the winding area is adequate, after an allowance for isolation spacing has been made.

**Step** 4. Calculate the minimum permitted drive pulse for safe turn-off. Example: Because this design relies on the transformer magnetizing energy to switch off the power MOSFET, a minimum drive pulse must be defined whereby the magnetizing energy equals the worst case turn-off energy for the MOSFET. Turn-off energy requirements for the MOSFET = $Q_G\cdot\Delta$ V where Qo is the maximum gate charge figure.

$\Delta$**V** is the gate voltage swing =30V
Magnetizing energy in the transformer

$$= (V_{IN}\cdot t_{on}min)^2/L_M$$

where $t_{on}$**min** is the duration of the minimum drive pulse. Equating these figures, assuming Qo = 17 nC for the IRF720 device, gives a minimum drive pulse of $t_{on}$**min** = 2.15 microseconds, which represents a minimum duty cycle, at 50 of 0.22.

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