

## **TRANSFORMER DESIGN FOR CHARGING DEFIBRILLATOR CAPACITORS**

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Generating high voltage by means of flyback topology is a common approach. Using the generated voltage to charge a capacitor for a high energy pulse are used in defibrillators, photo-flashes, strobes and ignition circuits to name a few. The procedure outlined in this article is useful in the initial transformer design phase for charging a capacitor in a stated time. The procedure presented eliminates “cut and try” or over-design approaches. Selection of critical values can be made with confidence using the guidance provided.

First a little background in flyback topology.

Flyback topology has several advantages -

- 1) Simple circuit.
- 2) High voltage output is not dependent on large turns ratios.
- 3) Circuit is self limiting. Output can be shorted without damage.
- 4) Output can be regulated over a large range.
- 5) Transformer can provide voltage isolation.
- 6) Multiple isolated outputs are possible. One output can be used for a low ratio feedback voltage.
- 7) Smoothing choke not required.

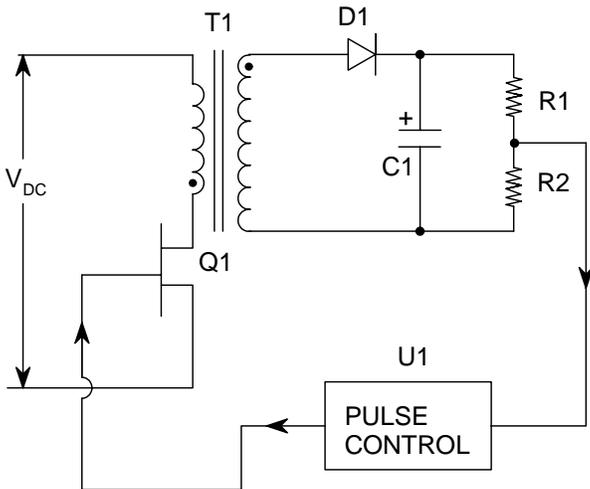
Some disadvantages -

- 1) Requires a transformer.
- 2) Fast switching can generate EMI problems.
- 3) Leakage inductance must be kept low for good efficiency.
- 4) Without a feedback loop, circuit may be damaged if the load is removed.

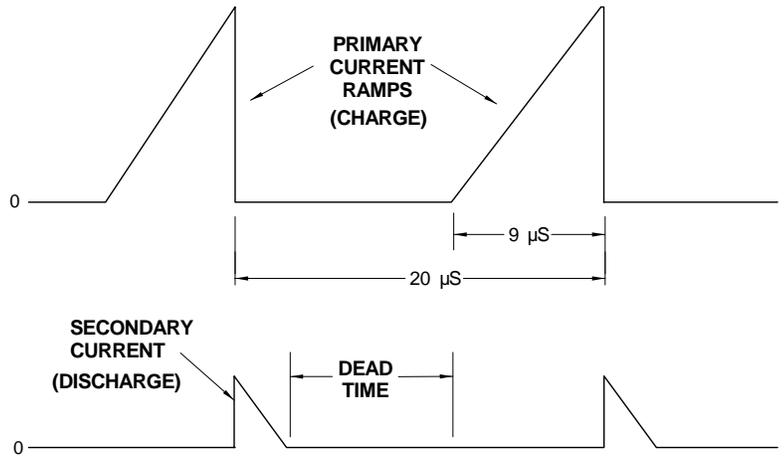
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Figure 1 below shows a simplified circuit. Figure 2 shows idealized waveforms.



**Figure 1**



**Figure 2**

The flyback operates by storing energy on the “charge” portion of the cycle and delivers the stored energy to the load on the discharge cycle. In the case of a flyback, the “transformer” is often described as a coupled inductor. Due to the diode polarity, current only flows in the secondary side during discharge. During the charge cycle, energy is stored in the primary inductance by a current ramp. The “dead time” shown in Figure 2 ensures that the flyback is dis-continuous. As the capacitor approaches full charge, the dead time increases. The current ramp follows the inductance formula F(1):

$$F(1) \quad L = \frac{V(\Delta t)}{(\Delta i)}$$

Where L is the inductance in henries, V is the applied voltage, ( $\Delta t$ ) is the time from the start to the end of the applied pulse and ( $\Delta i$ ) is the change in current over the same interval. If I starts at 0 (zero), delta I is equal to the peak current.

$$F(2) \quad I(\text{peak}) = \frac{V(\Delta t)}{L}$$

F(2) is F(1) solved for I(peak).  
For example: If V = 12 volts, time is 0 to 15 uS and L= 60 uH, peak I = 3.0 amps.

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The energy stored in the inductance is:

$$\mathbf{F(3)} \quad J = \frac{L(I_p)^2}{2}$$

Where energy J is in Joules, L is in henries and  $I_p$  is the peak current in amps. In the example above, the energy stored in each pulse is 270 uJ (micro-joules)

It is during the discharge of this stored energy that the greatest advantage of the flyback is realized. The output voltage will rise to whatever level is needed to cause current to flow, thus dissipating the stored energy. The voltage of the output has limits to be sure, but within the insulation structure, circuit design and taking losses into account the voltage can rise to very high levels. (The most common example, though ancient technology now, was the flyback transformer in color televisions with a CRT. These transformers could generate voltages greater than 35,000 volts. Voltages so high that if the circuits malfunctioned, the television could generate damaging X-rays. The analysis is somewhat simplified because the TV flyback transformer performs more functions than just generating high voltage.) The design of the flyback circuit and transformer for power transformation is well illustrated in Pressman's book "Switching Power Supply Design".<sup>①</sup>

The block in Figure 1 labeled "Pulse Control" can take many forms. In a defibrillator, pulse control will be a voltage feedback loop that fixes the number of joules to be delivered to the patient. During successive resuscitation attempts the level will increase. For photoflash the charge level is fixed. The capacitor will be charged and additional pulses will only be applied as a "refresh". In photoflash applications the "dead time" may be limited to speed up the charge time. The low dead time and variable discharge produces the characteristic increasing high pitch sound. Variations in the pulse control element are almost endless.

With the background provided, we can now tackle the problem of charging a capacitor to a given voltage in a stated amount of time. Designs begin with a list of known values. Below is an example of a typical design problem. The application is for charging a defibrillator capacitor. The example will be used to illustrate the process.

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**CAUTION: The charged capacitor used in the example can provide a LETHAL shock.**

Capacitor	=	100 uF
Charge Voltage	=	2,000 VDC
Charge Time	=	10 Seconds
Circuit	=	Discontinuous mode flyback
Frequency	=	50 KHz
Maximum duty cycle	=	45%
Maximum "on" time	=	9 uS (delta t)
Input voltage	=	12 VDC
Efficiency	=	See Step (4) and Figure 3
Primary Inductance	=	TBD
Peak Current	=	TBD

## Step (1)

Determine the number of joules required to charge the capacitor.

$$\mathbf{F(4)} \quad J = \frac{C(V)^2}{2}$$

Where J is in joules, V is the capacitor voltage and C is the capacitance in farads.

$$J = \frac{100 \times 10^{-6} (2000)^2}{2}$$

$$J = 200 \text{ Joules}$$

## Step (2)

Calculate number of charging pulses in the stated time.

$$\mathbf{F(5)} \quad \text{Number of pulses (N)} = 10 \text{ seconds} \times 50,000 \text{ pulses per second}$$

$$N = 500,000$$

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## Step (3)

Calculate the energy required per charging pulse

$$F(6) \quad \text{Energy per pulse (J)} = \frac{\text{Joules}}{N}$$

$$J = \frac{200}{500,000}$$

$$J = 400 \text{ uJ / pulse}$$

## Step (4)

Make an estimate of the circuit efficiency and include the factor in calculating the energy that must be supplied. All calculations up to this point assumed that there were no losses in the switching transistor, diode, and transformer (winding or core). The losses listed will occur (first order) plus losses in the winding capacitance and leakage inductance (second order). Figure 3 provides an estimation of a typical loss factor expressed as an efficiency figure. The losses must be included in the power supplied from the DC source. The calculation is shown below. Note that Figure 3 is an estimate and results will vary (like those diet pills). Use the joules calculated in F(4) to find the efficiency value. A number of variables in circuit design, layout, transformer design, components, etc., will effect the result. (For very high voltage designs, even the leakage current paths across the surface of the PC board and leakage within the capacitor must be considered.)

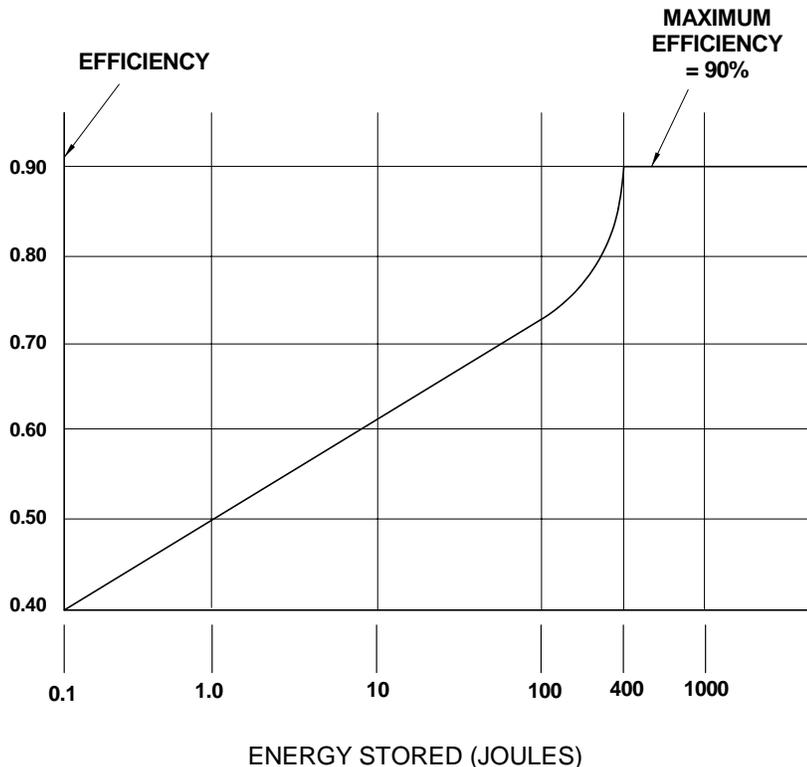


Figure 3

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$$\mathbf{F(7)} \quad \frac{\text{Joules per Pulse}}{\text{Efficiency}} = \text{Joules from DC source}$$

$$\frac{400 \text{ uJ}}{.8} = 500 \text{ uJ/Pulse (500 micro-joules per pulse)}$$

Step (5)

Solve for the unknowns. There are two unknowns and two formulas previously presented that will provide the answer. The unknowns are transformer primary inductance and peak current. The 500 uJ figure above can be solved with an almost infinite number of solutions. The remainder of the design requirements and the 500 uJ figure limits the answer to one solution. The process is shown below. Formula (1) is an inductance formula. Formula (3) is solved for the inductance. The right hand sides are now both equal to the inductance and the two expressions are set equal to each other. The resulting expression, with only one unknown, can be solved for the peak current. Having found the peak current, the value is entered into the original equation and solved for the inductance. For a “sanity check” both formulas are solved for the inductance. The equal results provide confidence that the calculations were performed correctly.

$$\mathbf{F(1)} \quad L = \frac{E\Delta t}{\Delta i}$$

Note:  $\Delta I = I$  (peak)

$$L = \frac{12 (9 \times 10^{-6})}{I_p}$$

$$\mathbf{F(3)} \quad J = \frac{LI_p^2}{2}$$

Solve for L

$$L = \frac{2J}{I_p^2}$$

$$L = \frac{2 (500 \times 10^{-6})}{I_p^2}$$

$$\frac{12 (9 \times 10^{-6})}{I_p} = \frac{2 (500 \times 10^{-6})}{I_p^2}$$

$$\frac{1.08 \times 10^{-4}}{I_p} = \frac{1 \times 10^{-3}}{I_p^2}$$

$$\frac{I_p^2}{I_p} = \frac{1 \times 10^{-3}}{1.08 \times 10^{-4}}$$

$$I_p = 9.259 \text{ AMPS}$$

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Calculate inductance “L” by substituting the value of  $I_p$  in both equations F(1) and F(3) as a check.

$$\begin{array}{l|l} \mathbf{F(1)} & \mathbf{F(3)} \\ L = \frac{12 (9 \times 10^{-6})}{9.259} & L = \frac{2 (500 \times 10^{-6})}{(9.259)^2} \\ L = 11.66 \mu\text{H} & L = 11.66 \mu\text{H} \end{array}$$

Figure 4 is the completed design with the calculated values included.

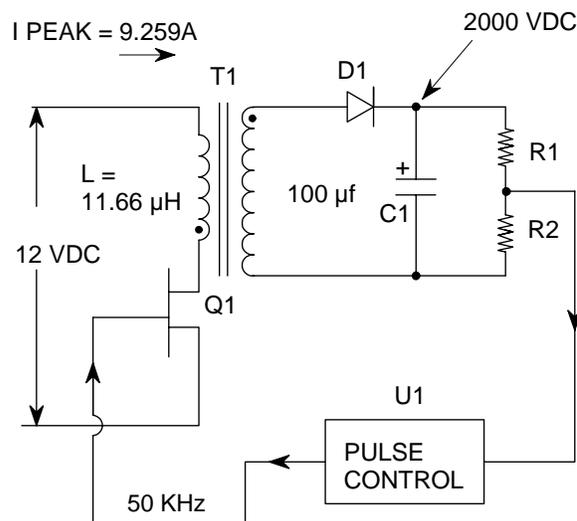


Figure 4

The procedure presented is not limited to charging a very large capacitor as in a defibrillator application. Charging circuits for smaller capacitors like those used in photoflash applications or smaller yet like those used in firing squibs can easily be designed. The procedure is not limited in frequency of operation or peak currents. The formula can be manipulated to fix a variable and predict the effect on the remaining variables.

Selection of the transistor, diode, core, turns ratio and all other elements can now be made to complete the design.

## Reference:

- 1) Pressman, A.I., 1998, Switching Power Supply Design, 2<sup>nd</sup> Edition, McGraw-Hill, ISBN 0- 07-052236-7