Technical Note: 1

Designing CAPACITOR CHARGING POWER SUPPLIES
For Flash-pumped Pulsed Solid State Lasers

The power supply required to charge the energy storage capacitor is perhaps the most important of all the modules for the following reasons. The heart of the system is the *main power supply*, which is invariably a switched mode one used to charge an energy storage capacitor to a voltage so as to store the required quantum of energy per pulse to be delivered to the flash lamp. The main power supply is also called *capacitor charging power supply*. The capacitor must charge to the desired voltage in a certain time, which is at the most equal to the reciprocal of the repetition rate of the laser. In practice, it should be slightly less, allowing for some minimum time for flash lamp quenching. The average power that this supply is expected to deliver at its output is the product of the energy per pulse and the repetition rate. The power supply accounts for more than 90 per cent of the total electrical input to the system. The efficiency of this supply is therefore the prime determinant factor for the overall electrical efficiency of the laser. The conversion efficiency also directly affects the size and weight of the overall system, a parameter particularly important in the military applications of Q-switched, flash lamp pumped solid state lasers.

Designing an efficient capacitor charging unit for a high repetition rate flash lamp pumped laser is not so simple an exercise as is seen from the discussion in the paragraphs to follow. The problem arises from the capacitive nature of the load. The power supply output needs to charge a high-value capacitor, typically 20 μF to 50 μF in case of designators and range finders and as high as thousands of microfarads in high-power pulsed lasers producing laser pulse energies of several kilo-joules meant for electro-optic countermeasures (EOCM) and laser weapon applications. In the following paragraphs are examined some circuit configurations that could possibly be used for designing the capacitor charging power supplies.

The simplest of the capacitor charging power supply may be configured around a transformer-rectifier arrangement of an AC-DC power supply as shown in **Figure 1.1**. Resistor (R_1) is the current limiting resistor to limit the charging current at the start of the charging process when the energy storage capacitor (C_1) is fully discharged. The semiconductor switch, typically an SCR, is used to turn-off the charging process when the capacitor is charged to the desired output voltage. The turn-on and turn-off of this switch is controlled by the output of the comparator. One of the inputs to the comparator is tied to a reference voltage and the other input is applied a fraction of the output voltage through potential divider arrangement of (R_2) and (R_3). The desired output voltage can be changed by changing either the reference voltage or the potential divider ratio.

Such a circuit becomes increasingly inefficient due to increased losses in the current limiting resistor when the laser is to operate at a higher pulse repetition frequency (PRF). At higher PRF, the charging current needs to be higher to charge the energy storage capacitor faster due to relatively smaller inter-pulse period. One way to overcome this problem is to use inductive current limiting as shown in Fig. 7.12. Here, the inductive reactance is used to limit the charging current.

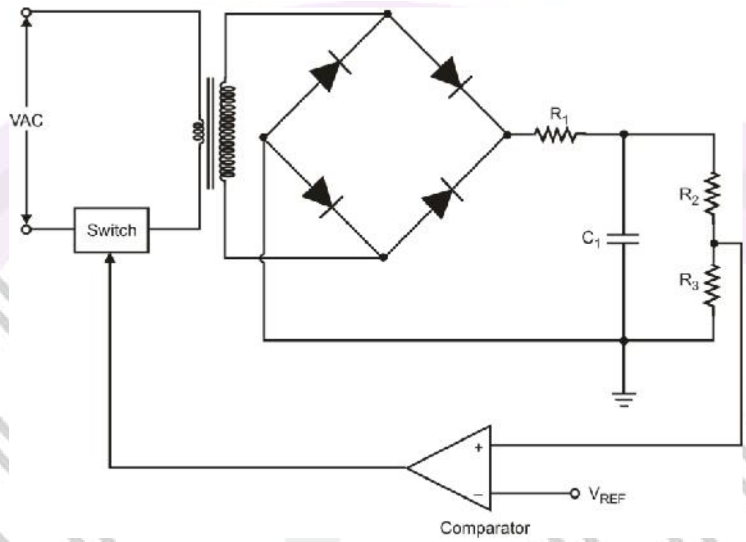

Figure 1.1
Simple capacitor charging power supply with resistive current limiting

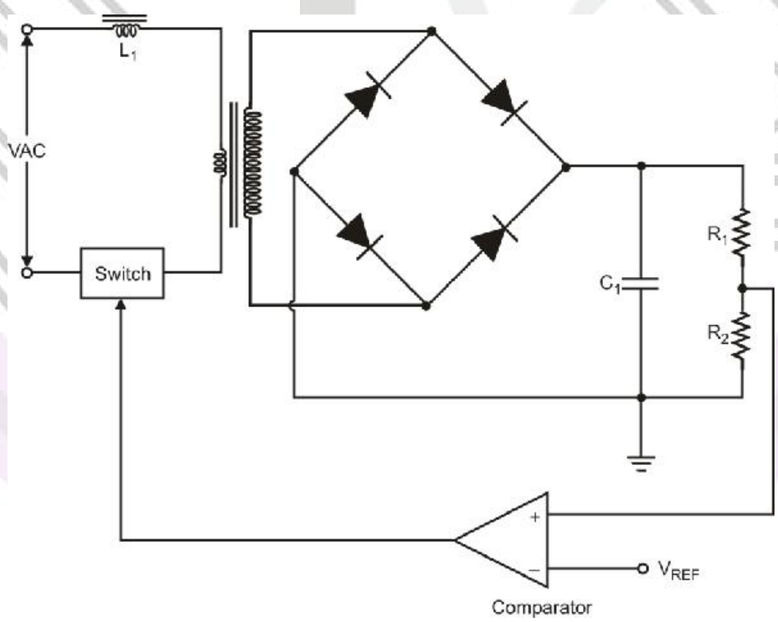

Figure 1.2
Simple capacitor charging power supply with inductive current limiting

Circuit configurations of **Figures 1.1** and **1.2** become ineffective when PRF becomes still higher and approaches the power line frequency. In that case, few cycles of power line frequency fall within the charging period with the result that the charging current is in the form current surges, one current surge for each half cycle. This renders the charging process erratic and irreproducible due to fluctuations in the number of current surges appearing in the inter pulse time period.

Resonant converter overcomes this problem. **Figure 1.3** shows the basic circuit. In this case, (C_1) is much larger than the energy storage capacitor (C_2) and acts like a filter capacitor. The energy storage capacitor is charged to twice the source voltage in the first half cycle of the resonant frequency. Diode (D_1) prevents any flow of current in the reverse direction when the capacitor is charged to a voltage higher than the source voltage. The diode also allows the designer to choose the discharge rate of the capacitor independent of the resonant frequency.

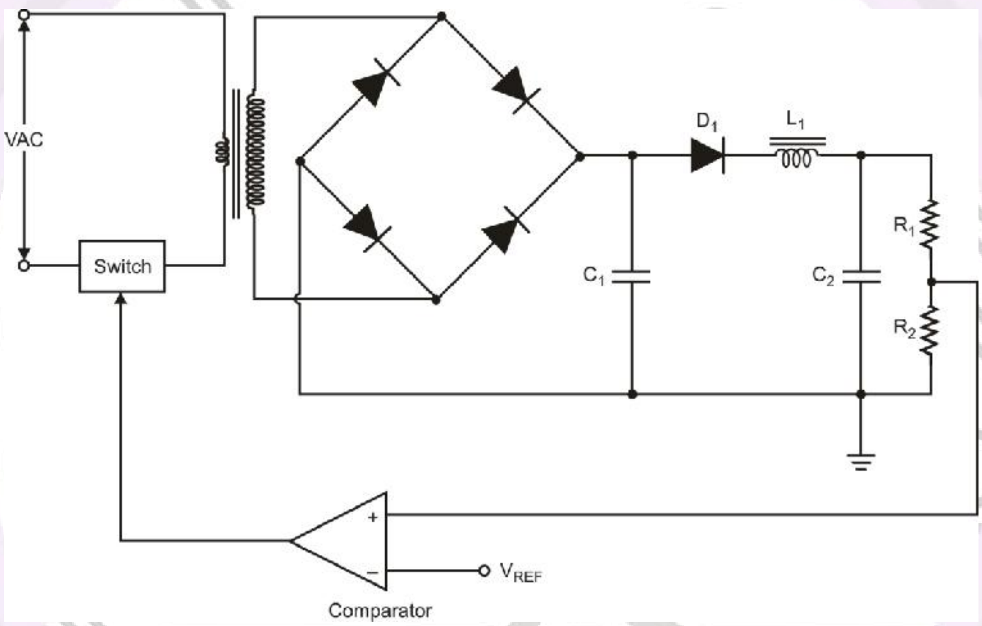

Figure 1.3
Resonant charging power supply

In the case of circuit configurations discussed in the preceding paragraphs, the AC to DC conversion occurs at power line frequency, which makes them bulkier and inefficient. Modern capacitor charging power supplies invariably use switched mode power supply concepts to derive the benefits inherent to these supplies. These include relatively much higher conversion efficiency and reduced size and weight. In addition, the source of input power could be either AC in off-line switching supplies or DC depending upon the intended application. DC as input source of power is particularly attractive for portable and military laser systems. An overview of different switching supply configurations along with their merits/demerits was given in chapter-6. Externally driven flyback converter suits the capacitor charging power supply requirements the best as it allows the designer an independent control on the ON and OFF times of the switching device. This feature is an asset as would be evident from the discussion that follows.

Figure 1.4 shows the basic circuit of an externally driven DC/DC converter. In such a case, where a flyback converter of the type shown in **Figure 1.4** is to charge an energy storage capacitor, the design is not as straightforward as it would be had there been a resistive load. The problem arises because of two reasons. The first is the fundamental fact that the voltage across a capacitor cannot change instantaneously and the other is that for a given voltage to be transferred to a capacitor, the quantum by which the capacitor voltage would increase depends upon the initial voltage across the capacitor just before the energy transfer. In fact, it is inversely proportional to the initial voltage across the capacitor, which implies that the time required to transfer a given energy to a capacitor would be decreasing with the build-up of voltage across the capacitor. This prohibits the designer to design the capacitor charging unit around a fixed switching frequency.

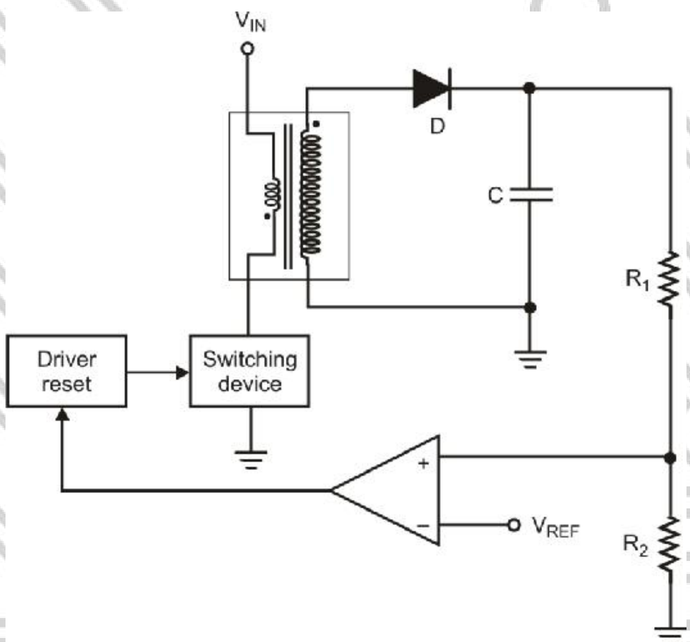

Figure 1.4
Simple externally flyback DC/DC converter as capacitor charging power supply

To do an optimum design, one needs to know the changing pattern of the voltage quantum and accordingly build a circuit that simulates these conditions. This problem is very specific to laser power supplies and no available SMPS controller chip can be used to do the job. It becomes more severe in case of portable systems where high conversion efficiency is of utmost important.

There are various circuit topologies available, such as flyback converters, forward converters, and push-pull converters, for designing a DC/DC converter. However, forward and push pull converters are suitable only for those types of loads that are predominantly resistive such as those encountered in the power supplies designed for TVs, music systems, personal computers, test equipment, and so on.

These types cannot be used in solid state laser capacitor-charging power source where the voltage across the energy storage capacitor builds up in voltage packets of continuously varying sizes with the energy transferred in each packet remaining the same. The first voltage packet is the largest and the last packet that takes the capacitor voltage to the desired value the smallest.

Such a load necessitates an independent control on the energy transfer time in accordance with the pattern of voltage build-up across the capacitor for an optimum power conversion. It is theoretically feasible to have such a control in a flyback converter where the energy is stored during the ON-time of the switching device and transferred during its OFF-time.

While in case of resistive loads it is the voltage regulation that is of prime concern and is achieved by some form of duty-cycle control, usually PWM, in case of capacitive loads the energy transfer process is a critical factor. An externally driven flyback converter seems to be the best bet for this application. But then, one needs to know the entire energy storage and transfer process, particularly the energy transfer times required in different discrete packets. Having known all that, one needs to think of an appropriate control circuit that would simulate the desired switching waveform. What the desired switching waveform looks like is explained in the following paragraph.

As we know in a flyback converter, during the ON-time of the switching device (bipolar junction transistor or MOSFET), primary of the switching transformer stores energy equal to $1/2\left(LI_P^{\ 2}\right)$ where (L) is the primary inductance and (I_P) is the peak primary current. This energy is transferred to the energy storage capacitor to charge it to a certain voltage during the switch-off time of the switching device. In a lossless and complete transfer of energy, the magnetic energy stored in the primary equals the electrostatic energy stored in the capacitor. Number of switching cycles required to charge the capacitor to the desired output voltage (V_O) can be computed from the ratio of energy stored in the capacitor at the final voltage $\left[1/2\left(CV_O^{\ 2}\right)\right]$ to the energy stored in each switching cycle $\left[1/2\left(LI_P^{\ 2}\right)\right]$. The size of the voltage packet received by the capacitor follows a decreasing pattern beginning with the largest in the first cycle as is evident from simple calculations given as under.

The voltage packet received by the capacitor in the first cycle when it is fully discharged can be computed from equation 1.1.

:

$$1/2\left(LI_P^{\ 2}\right)=1/2\left(CV_1^{\ 2}\right) \qquad \text{……1.1}$$

WhereV_1 is size of the first voltage packet

This gives

$$V_1 = I_P \times \sqrt{L/C} \qquad \text{.......1.2}$$

This is also the voltage across the energy storage capacitor at the end of the first cycle. The voltage packet received by capacitor during the second cycle when it is initially charged to voltage V_1 is given by equation 1.3.

$$1/2\left(LI_P{}^2\right) = 1/2\left(CV_2{}^2\right) - 1/2\left(CV_1{}^2\right) \qquad \text{.........1.3}$$

With help of simple mathematics, it can be shown that the voltage across the capacitor at the end of second cycle is given by equation 1.4.

$$V_2 = V_1 \times \sqrt{2} \qquad \text{..........1.4}$$

Similarly, the voltage across the capacitor at the end of third, fourth and Nth cycles shall be given by equations 1.5, 1.6 and 1.7 respectively.

$$V_3 = V_1 \times \sqrt{3} \qquad \text{...........1.5}$$

$$V_4 = V_1 \times \sqrt{4} \qquad \text{............1.6}$$

$$V_O = V_1 \times \sqrt{N} \qquad \text{.............1.7}$$

Where,
N is the number of cycles to charge the capacitor to voltage (V_O)

The value of N can be calculated from equation 1.7 and is given by equation 1.8.

$$N = \left(\frac{V_O}{V_1}\right)^2 \qquad \text{.............1.8}$$

Also,

$$N = \left(\frac{CV_O{}^2}{LI_P{}^2}\right) = \left(\frac{V_O}{V_1}\right)^2$$, which validates the expression.

Size of different voltage packets is given by equations 1.9, 1.10, 1.11 and 1.12 respectively.

$$Size \quad of \quad first \quad packet = V_1 \qquad \text{............1.9}$$

$$Size \quad of \quad second \quad packet = \sqrt{2}V_1 - V_1 = \left(\sqrt{2} - \sqrt{1}\right)V_1 \qquad \text{...........1.10}$$

$$Size \quad of \quad third \quad packet = \left(\sqrt{3} - \sqrt{2}\right)V_1 \qquad \text{............1.11}$$

$$Size \quad of \quad Nth \quad packet = \left[\sqrt{N} - \sqrt{(N-1)}\right]V_1 \qquad \text{...........1.12}$$

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It is evident from the above equations that the voltage packet size reduces in successive cycles with the build up of voltage across the energy storage capacitor. The time period required to transfer energy in each cycle depends upon the corresponding voltage packet it imparts to the capacitor. Therefore, one cannot use a fixed switching frequency. Ideally, the drive waveform must have a variable OFF-time beginning with the largest value and then decreasing in a well defined pattern. It is because of this that the flyback configuration of Figure 1.4 is not effective. A relatively lower switching frequency to allow complete energy transfer in the few initial cycles where large off-time is required leads to low conversion efficiency as in that case the converter is sitting idle for most of the time in the latter cycles. Use of a relatively higher switching frequency leads to incomplete energy transfer in the initial cycles which in turn reduces the conversion efficiency. In addition, incomplete energy transfer in a flyback converter could cause damage to the switching device. Figure 1.5 shows the modified schematic of flyback converter based capacitor charging power supply that takes care of variable OFF-time requirement. The circuit operates as follows.

The basic difference between the block schematic of Figure 1.5 and the conventional externally driven flyback converter configuration of Figure 1.4 lies in the mechanism of generating the drive signal waveform for the switching device. The *drive portion* of the converter hardware comprises of a cascaded arrangement of a voltage controlled oscillator (VCO), a monoshot circuit and a drive circuit. Output of VCO feeds the trigger input of the monoshot. The pulse width of the monoshot is chosen to be equal to the desired ON-time of the switching device. The frequency of monoshot output and hence the OFF-time of the waveform is governed by the frequency of the VCO output, which in turn depends upon the voltage applied to its control input. The drive circuit provides the required drive current and/or voltage depending upon the type of switching device used.

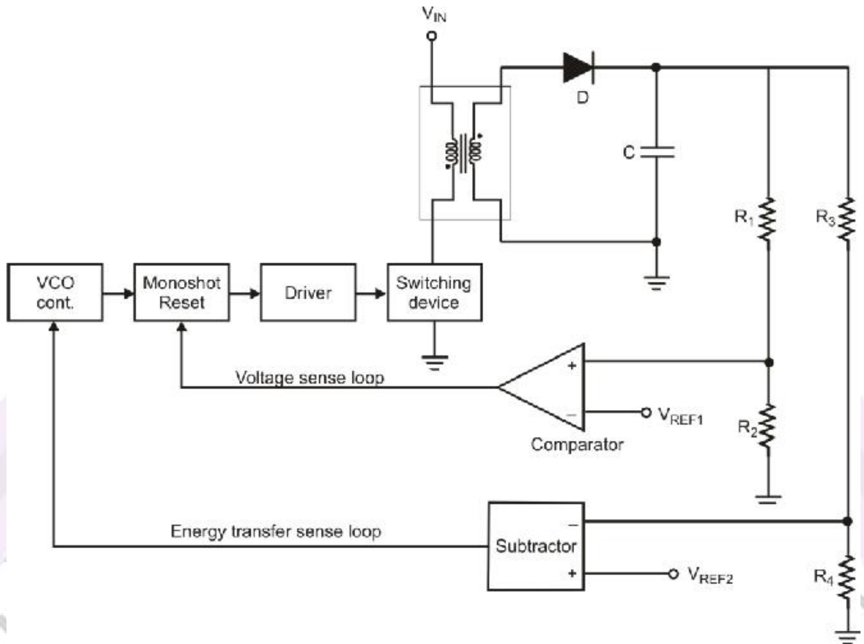

Figure 1.5
Modified flyback DC to DC converter as capacitor charging power supply

The *feedback circuit* comprises of two independent potential divider arrangements, a subtractor circuit and a comparator circuit. Potential divider R_1-R_2 along with the comparator constitutes the voltage sense loop. The output of the comparator circuit resets the monoshot when the energy storage capacitor has charged to the desired voltage. Due to this feedback loop, the voltage across the capacitor remains around the desired value with the output ripple amplitude depending upon the minimum input differential required by the comparator to change state at the output and the dividing factor of the potential divider R_1-R_2. As an example, for an output voltage of 1000 V, one may use a dividing factor of 200 to bring it down to 5 V; an input differential of 5 mV shall lead to peak-to-peak ripple amplitude of 1 V. Potential divider R_3-R_4 along with subtractor constitutes the energy transfer sense loop. That is, it is instrumental in generating the desired variable OFF-time pattern in the drive waveform to ensure complete or nearly complete energy transfer in different cycles. The subtractor output feeds the control terminal of the VCO. The voltage present at the output of the subtractor is a function of the output voltage. Output frequency of VCO depends upon the control voltage. The components of the frequency determinant network of the VCO are so chosen that for the energy storage capacitor in fully discharged condition, the voltage present at subtractor output produces VCO output of desired frequency that in turn produces the desired OFF-time for the first cycle of energy transfer. As the voltage across the capacitor builds up, the output of subtractor circuit changes in a manner as to change the drive frequency in the correct direction. That is, the VCO output frequency reduces in a pattern identical to the pattern of voltage build up across the capacitor. In a modification of the above design, the comparator, subtractor, VCO and the monoshot can be replaced by an embedded processor to generate the output waveform to be fed to the drive element.

What is described in the preceding paragraph is the qualitative description of the concept of having a variable off-time drive waveform in accordance with the mode of energy transfer in a capacitor charging power supply configured around an externally driven flyback converter. The author of the book has patented this design philosophy for use with capacitor charging power supplies for flash-pumped pulsed solid state lasers. This design methodology has been used by the author to design a range of high efficiency capacitor charging modules with different Joules/second delivery ratings for various laser applications.

