Lasers in Manufacturing Conference 2017

Power Management of Randomly Modulated and Pulsed Laser Systems

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Abstract

Laser System integrators are constantly faced with the necessity of optimization of electrical part of a system. This is especially difficult with randomly modulated and pulsed laser systems. Very often an electrical system has to handle tens (hundreds) of kilowatts of pulse power while average power consumption does not exceed small fraction of that level. Q-switched diode lasers, randomly modulated laser diode based systems, CO_2 lasers (in super-pulse mode), RF pumped CO_2 lasers and flash lamp pumped lasers are good examples of such kind of systems.

Usually, an intermediate energy storage device (capacitor) is used to mitigate high power needs but an electronics system intended to replenishing the energy in the intermediate storage device does not get deserved attention. As a result, the supply line experiences uneven power consumption, high peak currents and system generates a lot of electromagnetic noise (EMI). This, in turn, creates control and communication issues.

Supply power lines or DC sources (batteries) are supposed to see only average power consumption. This is especially important for battery powered systems.

This presentation is an attempt to address these issues and demonstrate that the power consumption averaging system is the path to laser system optimization for performance, efficiency, cost and size.

Keywords: System Technology, Process Control, Pulse Power, Efficiency, System Integration.

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1. QCW Systems

This presentation is intended to considering only loads requiring a current source for operation. Laser diodes is one of the best examples of such kind of loads. CO_2 lasers and flash lamps fall into this category as well.

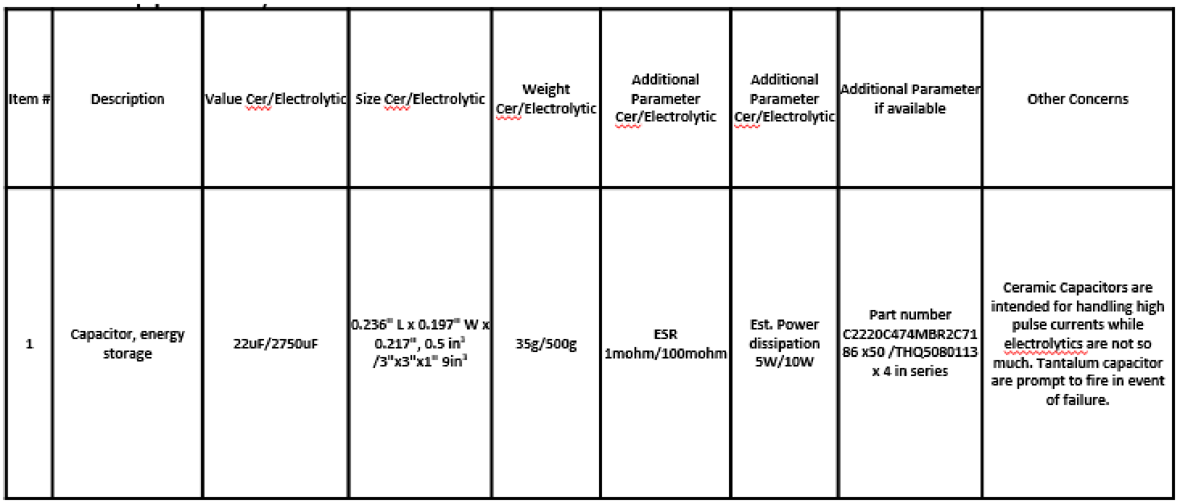
The general structure of power system with pulse/modulation capability is depicted on fig.1a and fig.1b.

For convenience, let’s concentrate on laser diodes related systems. The same principles, though, are applicable to other systems as well.

In QCW (quasi continuous wave) mode of operation a laser diode(s) can be pumped with tens of kilowatts (kW) of peak electrical power (via Laser Diode Driver (LDD)) while the average power consumption is on hundreds of watts level. The Duty cycle can vary from a fraction of percent to about 10%. Power to the LDD is supplied from the energy storage capacitor.

In an ideal world a system designer would need to utilize fully the energy storage capability of the energy storage capacitor intended for that. In the real life it is hardly possible. The capacitor size, weight and cost will depend on how much voltage swing is allowed during the discharge. The laser diode driver, if designed properly, can handle 2:1 voltage swing on the input while maintaining constant current through the laser diode. Which gives us about 75% of stored energy utilization of the capacitor. If this technique is used, the capacitor value can be reduced by factor of 3 – 4 which opens the door to use ceramic or film capacitors instead of electrolytic capacitors usually used in the application. This is extremely important in mission critical applications where the usage of electrolytic capacitors is undesirable. In reality the value of electrolytic caps is chosen to achieve low ESR (equivalent series resistance) and has nothing to do with capacitance, which is usually way bigger than required by the application. So, permitting substantial voltage swing on the energy storage capacitor allows a designer to reduce size, weight (by factor of about 10) and cost of the energy storage system supplying power to the laser diode driver. Table 1 gives a comparative example between an energy storage system based on electrolytic and ceramic capacitors.

Table 1. Comparison of Energy storage capacitors for QCW laser diode driving.



Item #	Description	Value Cer/Electrolytic	Size Cer/Electrolytic	Weight Cer/Electrolytic	Additional Parameter Cer/Electrolytic	Additional Parameter Cer/Electrolytic	Additional Parameter if available	Other Concerns
1	Capacitor, energy storage	22uF/2750uF	0.236" L x 0.197" W x 0.217", 0.5 in^3 /3"x3"x1" 9in^3	35g/500g	ESR 1mohm/100mohm	Est. Power dissipation 5W/10W	Part number C2220C474MBR2C7186 x50 /THQ5080113 x 4 in series	Ceramic Capacitors are intended for handling high pulse currents while electrolytics are not so much. Tantalum capacitor are prompt to fire in event of failure.

2. Power Supply Requirements.

It looks like that AC power system has natural advantage compare to DC one, namely, Power Factor Corrector (PFC). PFC has a large energy storage capacitor on the output (about 0.5µF - 1µF per watt of output power) which can potentially be used to power a pulsed LDD. There are several problems, though, associated with this approach. First, ESR of the filter capacitor is too high for pulsed LDD. Second, PFC does not allow substantial voltage drop for normal operation, so capacitor's energy utilization will be poor. It is conceivable to create a PFC circuit which can operate in the range of output voltages 1:2 (say, no load voltage is 800V while at 400V a PFC is still operational) but … such systems are not available on the market.

So, in AC as well as in DC arrangements an intermediate module (Bus Conditioning Module) is required to sustain the voltage on the energy storage capacitor.

This module can be a voltage source, current source or power source.

The purpose of this presentation is to identify which type of power supply is optimal for the application and gives advantages in terms of EMI/RFI generation, filter requirements, size and weight. We will compare the waveforms of the current consumed from the constant voltage source on Fig.1a in case of different Bus Conditioning Module configurations: Voltage Source, Current Source and Power Source.

Voltage Source (Ref. 1, K. C. A. Smith et al., 1992) used to supply power to a Laser Diode Driver will see ripple current equal to that of LDD. As soon as voltage on the energy storage capacitor starts dropping the Voltage Source will try to compensate the voltage drop with full necessary current. The current is only limited by the output impedance of an ideal voltage source which should be considered as Zero (Fig.2)

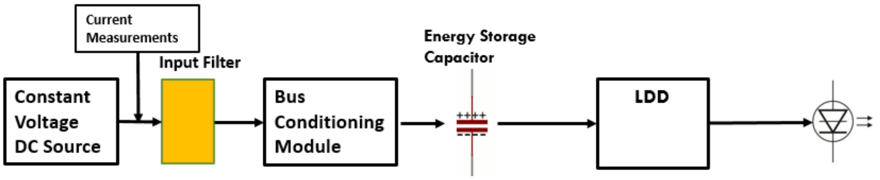


Fig. 1a

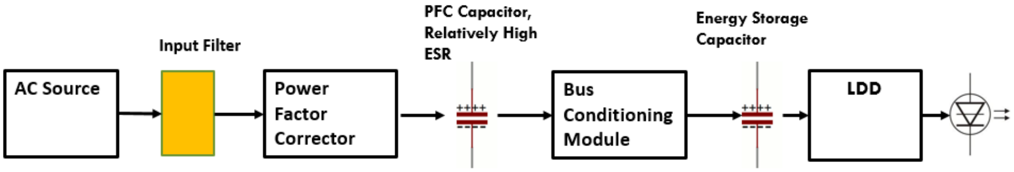


Fig. 1b

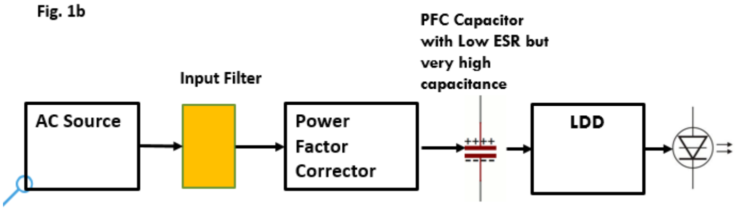


Fig. 1c

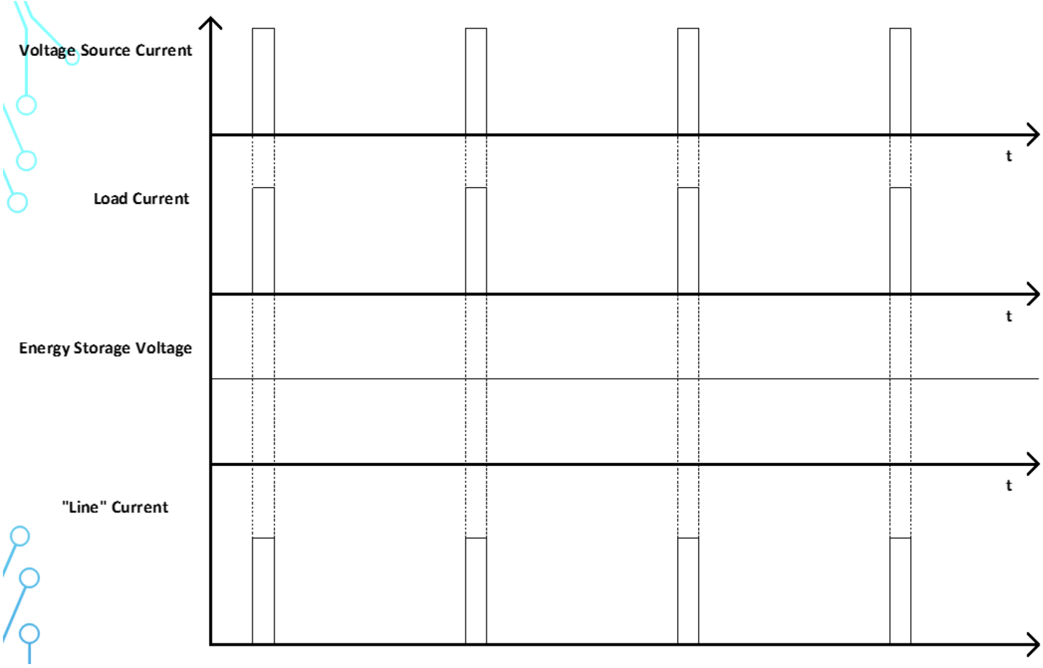


Fig. 2. Current ripple on the voltage source at the current measurement point of Fig. 1a (“Line” Current)

If Current Source (Ref. 3) is used to replenish the lost charge on the energy storage capacitor, it will also generate the current ripple in the feeding line. The matter is that the power consumption at the beginning of the charging cycle is only the half of that at the end of charging cycle. If we have a constant voltage source in front of Bus Conditioning Module, it will see current consumption swing equal to factor of 2 (again, it is assumed that allowed voltage swing on the energy storage capacitor is 2:1) (Fig.3).

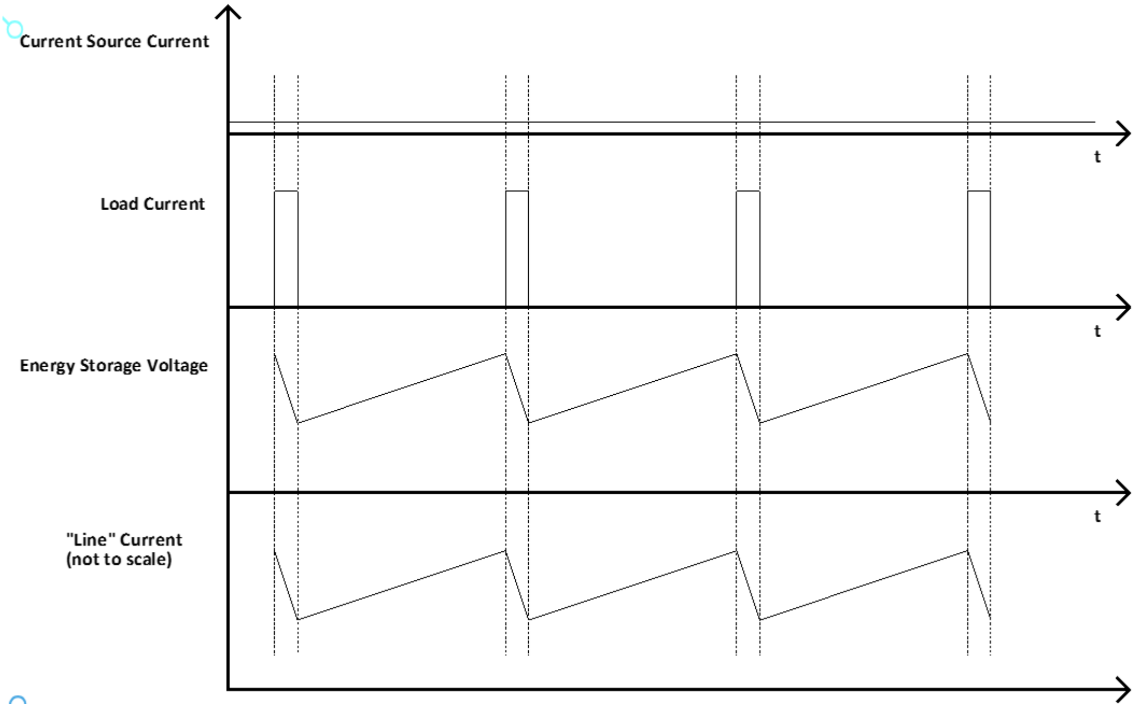


Fig. 3. Current ripple on the voltage source at the current measurement point of Fig. 1a (“Line” Current)

Let’s define a Power Source as a source of electrical power which delivers constant power to the load independent of the load value.

If **Power Source** is used to replenish the lost charge on the energy storage capacitor, it will generate … zero current ripple in the feeding line. The power source will deliver twice as high current at the beginning of the charge cycle compare to the end of charge cycle without changes in the current consumption from the line (Fig.4).

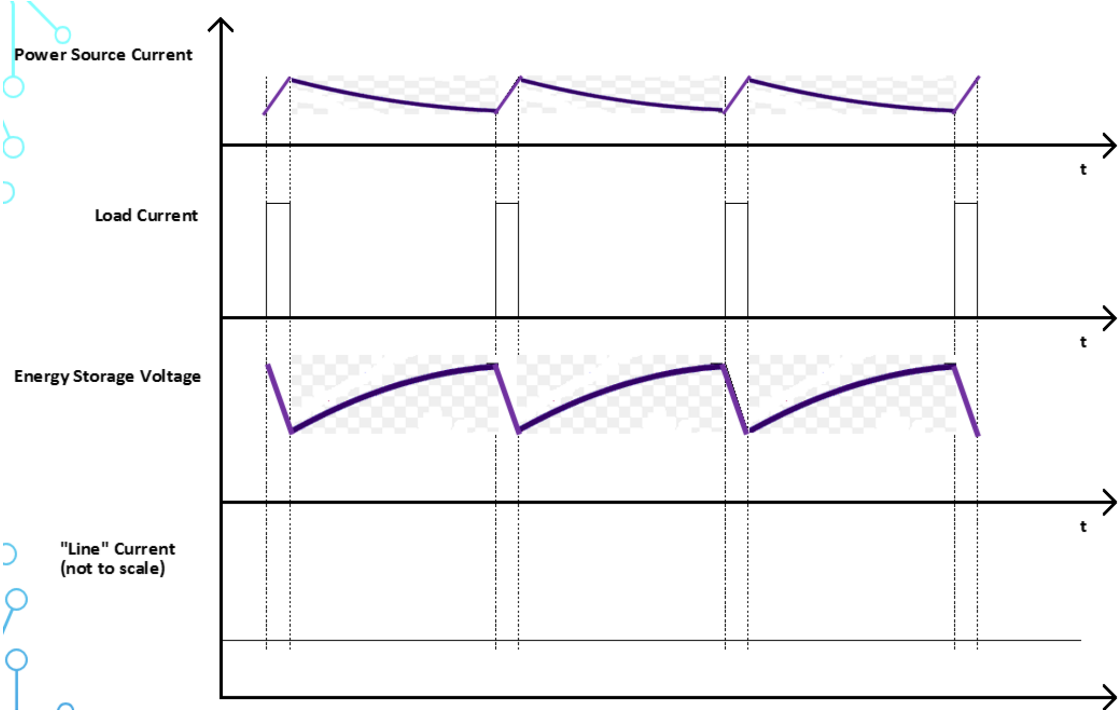


Fig. 4. Current ripple on the voltage source at the current measurement point of Fig. 1a (“Line” Current)

There is yet another advantage in utilization of power source topology in Bus Conditioning Module compare to a current source, namely, peak power consumption of a power source is smaller compare to voltage and current sources. In fact, there is no peak power consumption when power source is used. Power consumption is uniform during the operating period substantially reducing the requirements to the filtering and energy storage of Power Supplying system.

Quick practical example is described below. If a Duty Cycle is 1% the RMS current consumption, in case the voltage source is used, is $I_{peak}/10$ (or $10*I_{average}$) , in case the current source is used – $1.04*I_{average}$ (waveform on fig.3) and finally the power source has it equal to $I_{average}$. The ripple current is 100% in case the voltage source is used; it is 66% of $I_{average}$ in current source and no current ripple in case of power source. It can be seen that the filter for the power source should be designed only to filter out the switching frequency of the Bus Conditioning Module with no attention payed to Pulse Repetition Rate. The calculations are straightforward and simple and there is no need to concentrate on formulas.

So, the conclusion which can be drawn from above considerations is that the averaging the power consumption in the pulsed systems gives substantial advantages compare to other approaches in terms of system size, weight and performance.

Below are several examples of the circuits which can be used as a voltage, current and power sources. Due to the limited format of this paper there will be no detailed explanation on circuits operation but this topic can be discussed “off line”. Also, we will not discuss methods of how to guarantee “soft switching” in full range of operating conditions and what will it take to reach extreme frequencies of power conversion.

Traditional Series Resonant Converter (SRC) (Ref. 5 and R. King et al., 1981) is a good candidate to perform the duties of converting energy of constant voltage source which is located in front of Bus Conditioning Module into power source. Output power measurement (multiplication of output voltage and current) will be required to create a closed loop operation. The switching frequency in this case will lay in between resonant frequency (f_r) defined by L1r and (C1r + C2r) and $f_r/2$. This circuit is commonly used in capacitor charging power supplies for last several decades.

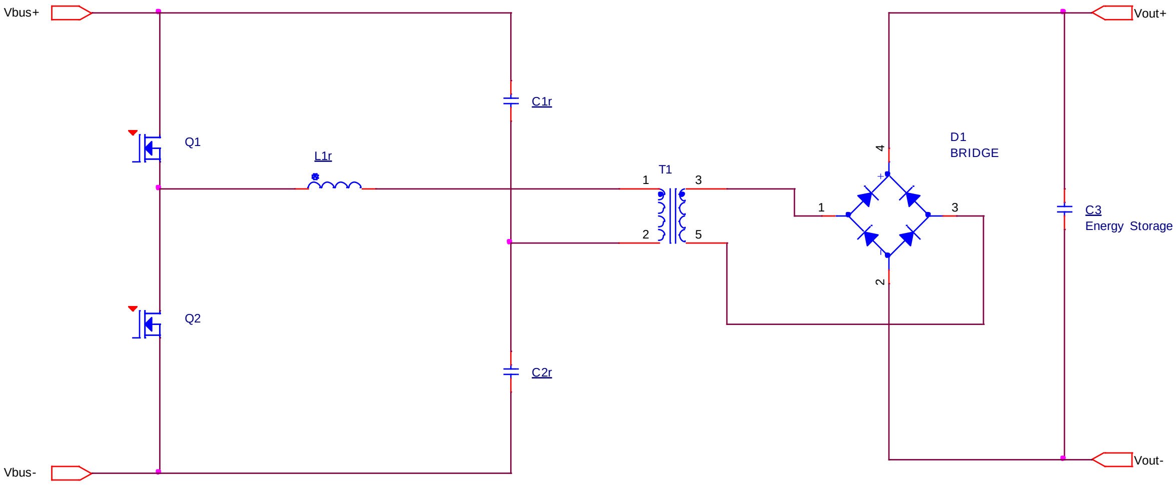


Fig.5. Series Resonant Converter

Another good candidate is the circuit depicted on Fig.6 (M. Borage., 2005). This resonant circuit has very interesting features because depending on switching frequency it can operate as a voltage, current or power source. At the switching frequency equal to resonant one defined by Lr1 and Cr the system behaves as a current source. At the switching frequency equal to $\sqrt{2}*f_r$ the circuit behaves as a voltage source. Using the power feedback loop (similar to SRC) and operating in between f_r and $\sqrt{2}*f_r$ it is possible to achieve a constant power control. Both circuits (Fig.5 and Fig.6) can be made short and open circuit protected. Also, both circuits utilize the parasitic parameters of the transformer using transformer's leakage inductance to improve the energy conversion efficiency.

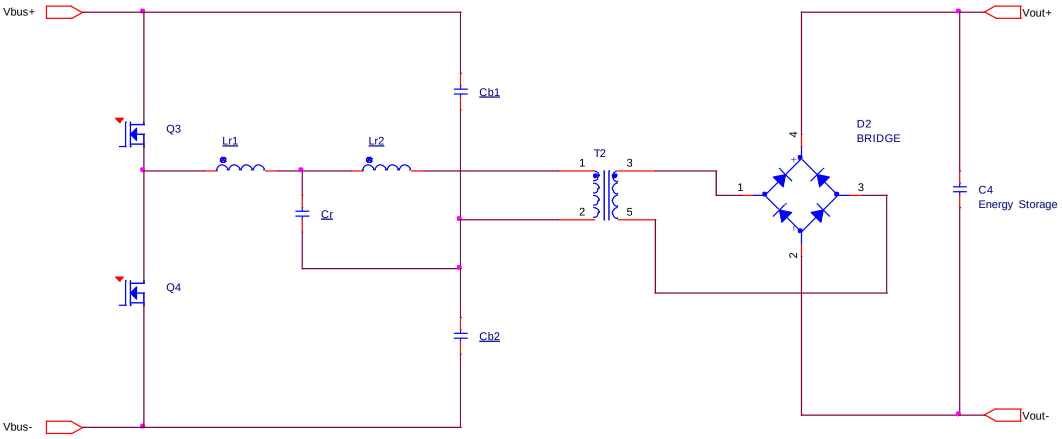


Fig.6. Resonant half bridge with T-filter as a resonant tank (LCL)

The circuit depicted on Fig.7 defers from 2 others because the voltage in front of the converter defines the maximum power available to the secondary side without using any feedback loop. Of course the power feedback loop will be required as operational conditions change but the converter on Fig. 7 plays a role of natural protector of the input voltage source preventing it from being overpowered at all operating conditions and with no feedback loop required.

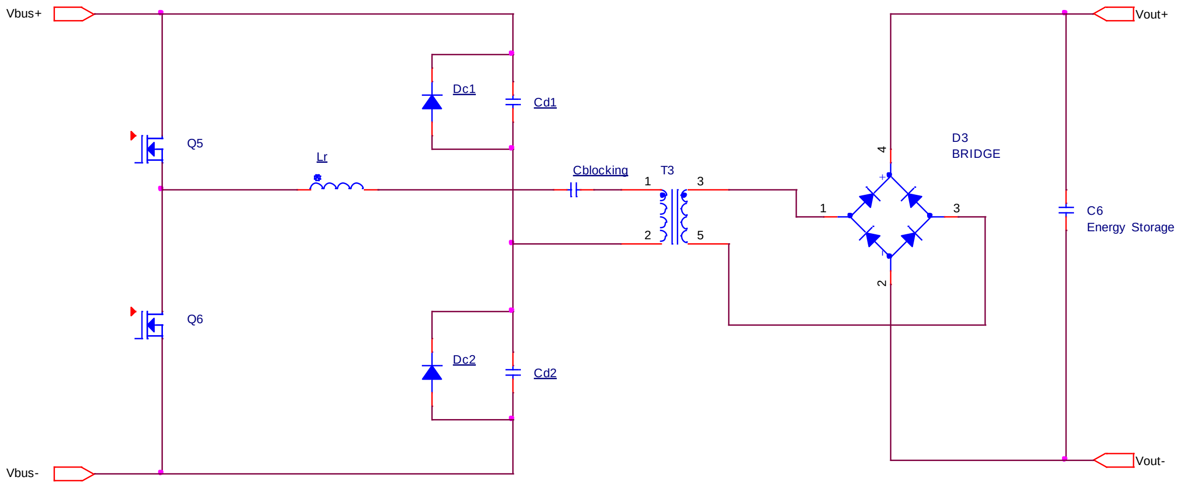


Fig. 7. Voltage to Power Converter in simplified form

This circuit was used in experimental capacitor charging power supply described by Pokryvailo et al., 2010 as well as in some other applications. The capacitors Cd1 and Cd2 are the “dosing” capacitors limiting the amount of energy which can be delivered to the output every half switching cycle. The range of the output voltages covered by “constant power delivery” mode of operation is defined by inductor L_r (which can be a leakage inductance of the transformer).

3. Randomly modulated diode laser systems

Randomly modulated diode laser systems present a special category which mixes pulse and CW modes of operation. They are used when application requires constant peak current yet variable output laser power (laser cutting for example). A system can go from CW to modulated mode (usually 2 – 5 kHz modulation frequency) very quickly and that is where right power management is important (as well as Laser Diode Drivers) to keep power consumption changes and electromagnetic interference (EMI) in check.

Separation of functions – current regulation and power consumption management – has to be addressed carefully in this application. The role of Laser Diode Driver (LDD) in this case is to maintain laser diode current conditions required by application while the role of Bus Conditioning Module is to slow adjust the power consumption from the line. In some cases, Power Factor Corrector (single or three phase one, application dependent) can perform these duties but in others a special Power Conditioning Module is required (battery powered systems).

In any event, a Power Conditioning Module built as a power source allows EMI reduction thus filter requirements can be substantially reduced.

The same power conversion topologies depicted on Fig.5 – 7 can be used in this application. Ones again, the limited format of this paper does not leave a room to discuss LDD design approach for Randomly Modulated Systems which presents a special interest.

In most of high power Laser Diode systems operating in this mode a power factor corrector is quite adequate for the role of Bus Conditioning Module since bus filter capacitors are supposed to be rated for peak power anyway. Only in very limited occasions where electrolytic capacitors cannot be used, ceramic ones take over.

Conclusion

Power Source (as defined above) has substantial advantage when it comes to the management of pulse and randomly modulated laser systems. When used properly, the discussed approach allows reduction of size, weight and cost of the power system overall. Unfortunately, there are very important supplemental topics intentionally omitted in this publication, namely, managing line/bus stability of laser systems and improving Power Factor of high power laser systems. It will be discussed in further publications

Acknowledgements

My sincere thanks to Grigoriy Trestman and Alexander (Sasha) Isurin (both power electronics professionals) for continuous support and informal discussions.

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