LED Systems-Constant Current vs. Constant Voltage

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High Brightness LEDs are commonly used in small and large signs and general lighting applications. LED Luminaire and system designers are routinely faced with tradeoff decisions concerning Cost, Efficiency, Reliability, Integration and Scalability, among other things. High Brightness LEDs used in such systems, like any other electrical component, are ruled by Voltage and Current, and as semiconductor material, LEDs have a non-linear (logarithmic) V-I relationship (Fig.1a). Due to the nonlinear behavior, a small voltage fluctuation will cause a relatively large current variation resulting in an unsafe operating current for the LED as well as a noticeable light output fluctuation. For those reasons the electrical power needed for driving LEDs is regulated by way of limiting the current through various techniques. This paper explores those techniques and explains the differences, advantages and disadvantages of each current limiting technique.

LED Module& Driver

Module-An LED module is a circuit board that contains LEDs. For functionality reasons, the LEDs are usually soldered onto Printed Circuit Boards (PCB), and in most cases for better thermal management LEDs are mounted onto Metal Core Printed Circuit Boards[1] (MCPCB). The PCB or MCPDB assemblies are referred to as LED Modules (Fig. 1b). An LED module can be powered by either a Constant Current or a Constant Voltage source. Efficiency of a CC LED module is nearly 100% (neglecting energy loss in the LEDs for the purpose of this paper)[§], where as CV Module Efficiency, $\mathbf{E_m}$, may be anywhere between 70% to 95%, with present technology, as seen in our calculations below.

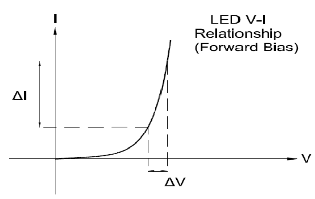
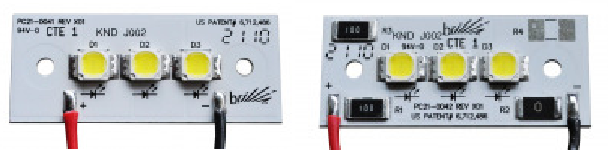


Fig.1a- A typical LED V-I Curve



(CC) (CV)

Fig. 1b- LED Modules: MCPCBs containing 3 LEDs

Driver-An LED driver is an electronic power supply that converts unregulated input (wall) power to a regulated output voltage or current that is compatible with the LED module design requirements (Fig.2b). Even though each LED is a "Current" device, the module must be powered by either a Constant Current (CC) driver or a Constant Voltage (CV) driver. With the present technology, CC drivers have efficiencies ranging between 80% and 95%, where as CV drivers' efficiency ranges between 80% and 85%. Most common CV drivers are 12Vdc and 24Vdc. Even with regulation, a CV or CC driver output will vary general by ±5%. So a 12Vdc CC driver can have anoutput voltage that may vary between 11.4Vdc and 12.6Vdc; and the output of a 350mA CC driver may fluctuate between 332mA and 368mA. Such fluctuations are commonly caused by component tolerance, temperature, input line fluctuations, or by components' aging.

Fig.2b- A CC driver

[1]*Permlight Patents 7,114,831; 7,594,740*

CC LED Module

A CC LED module usually contains only the LEDs as seen in Fig.1b-CC. The LEDs are electrically arranged in a manner which allows for passage of a safe amount of current through each LED. For example, Nichia specifies for its NS3W183 a maximum forward current $I_{f\ max}$=150mA and nominal forward voltage Spec. is V_f=3.0V. A safe current to operate this LED is 130mA or lower, as it will be shown later that a 5% driver output fluctuation can easily cause a 20% current fluctuation in the LED exceeding its max. allowable current. System efficiency is in general equal to the driver efficiency since CC module efficiency is 100%.[§]

Various CC Module Designs

Paragraphs a-d, and Figures 3a-d will explore various circuit configurations to achieve safe operating conditions for a CC LED module system. It is important to note that a CC driver and modules are a matched set. The design current of a module must equal that of the driver output and the voltage of the module must be within the range of output voltage of the driver.

a. In Series configuration of Fig.3a, current supplied by a 120mA driver passes through all 3 LEDs equally while the voltages add up. The LED module will require a constant current of 120mA (regulated) at about 9vdc. In this example the driver will produce afixed 120mA in output current but will have an output voltage range of 7 to 16 volts, making it a 2 watt driver.

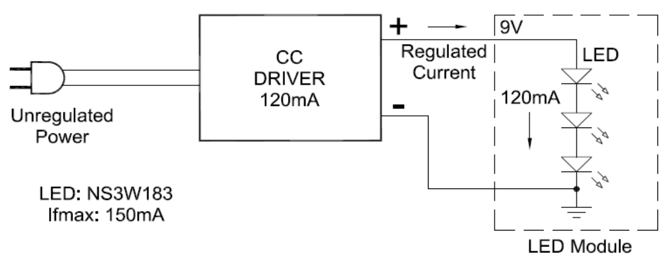


Fig. 3a- A 120mA/16V CC driver and module set with 3-in series design where voltages add up (3x3v=9V) but current stays the same at 120mA

b. In Parallel configuration, Fig. 3b, to maintain a safe 120mA current through each LED, we must use a 360mA driver with a lower voltage range of 2-5 volts. Here the current through each LED is 1/3 of the total supplied current (360 ÷ 3=120mA), but the voltage remains at 3V. This configuration is not used much due to precise V_f matching requirement for all LEDs in parallel. Instead a serial-parallel circuit is used as shown in 3c.

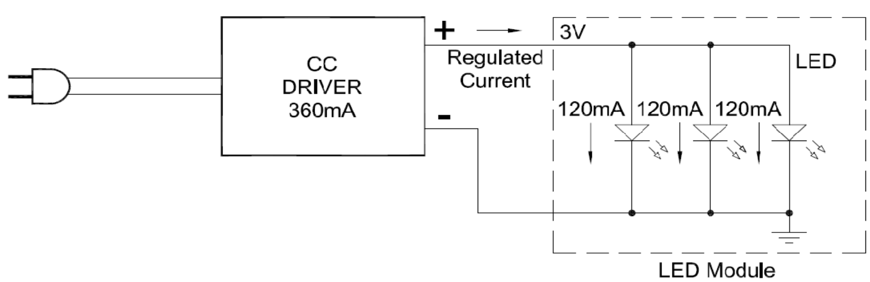


Figure 3b- A 360mA/5V CC driver and module set with 3-in parallel design where currents add up (3x120mA=360mA) but voltage stays the same at 3V

c. In a more popular Series-Parallel combination, Fig.3c, the module current equals sum of the currents flowing through all branches and the voltage is equal to sum of V_fs in one branch. So the module in this example will require a constant current of 360mA (regulated) at about 9vdc. Then the driver will only produce 360mA in current with an output voltage range of 7 to 16 volts, making it a 6 watt driver.

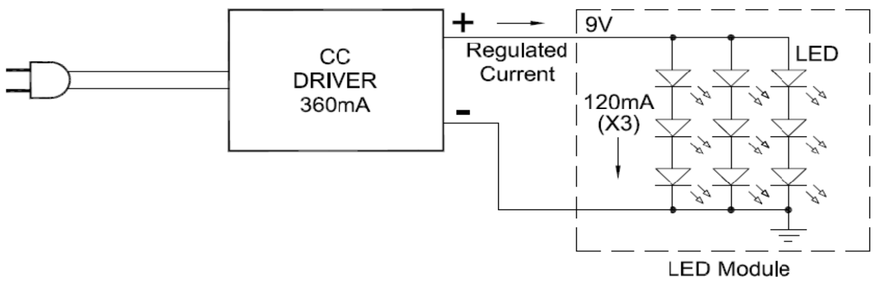


Fig. 3c- A 360mA/16V CC driver and module set with 3-in series x 3 in parallel design where both voltages currents add up (3x3v=9V) and (3x120mA=360mA)

Point of Use- Multiple CC modules may be connected in a series configuration powered by a single CC driver. In this case the total voltages of all modules must not exceed that of the driver. In Fig. 3d example, 3 of the modules in Fig. 3a are connected in series, requiring 9V+9V+9V=27Vdc (Fig. 3d), so the driver must be capable of supplying 120mA at a minimum voltage of 27 volts.

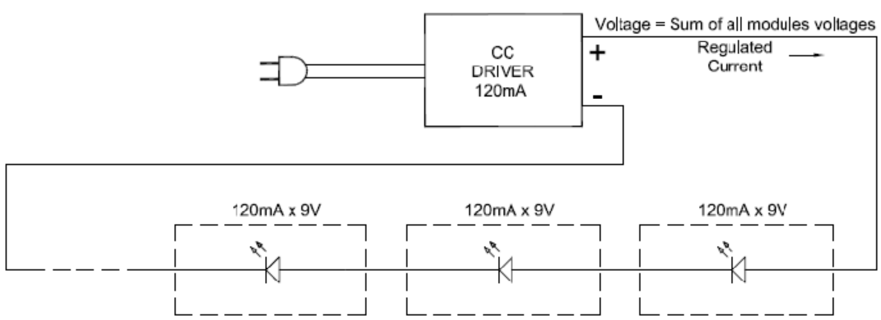


Fig. 3d- A 120mA CC driver-module set with 3 modules in series. Voltages add up (3x9v=27V) but current remains at 120mA

Pros and Cons of CC Modules

Pros: CC systems are generally very efficient since the system efficiency is equal to thatof the CC driver efficiency which is typically 80-95%.[§]

Parts count and system cost is low and LED brightness remains constant with longer wire lengths between the driver and the module.

5% driver output current fluctuation will translate to an imperceptible 3.5% in light output fluctuation.

Multiple CC modules may be connected in a series configuration, making the system scalable, while maintaining brightness uniformity throughout the chain of modules.

Cons: In a CC system the driver current and voltage range must be closely matched to that of the module(s) making interchangeability with alternate components somewhat difficult.

CC designs can dictate high operating voltages reaching hundreds of volts. This added safety concern then becomes costly to resolve, hence higher system cost and limited application.

CV LED Module

A Constant Voltage LED module is powered by a driver that has a fixed voltage output over a small range of currents. Because the LEDs are "Current" devices, most CV Modulesare designed using one of the following current limiting techniques to ensure that LEDs operate at the safe operating current:

1. Resistive Current Limiting
2. Active Linear Current Limiting
3. CC Buck-Boost Driver (on the module) Current Limiting

1-Resistive Current Limiting- In Resistive Current limiting method the LEDs are placed in series with a resistor R, designed to drop the supplied voltage to the nominal voltage level of the LEDs V_F at the design current I_f (fig4a). Even though the current is matched to the LED, if the input voltage fluctuates slightly, the LED current will vary linearly (Fig. 4b).

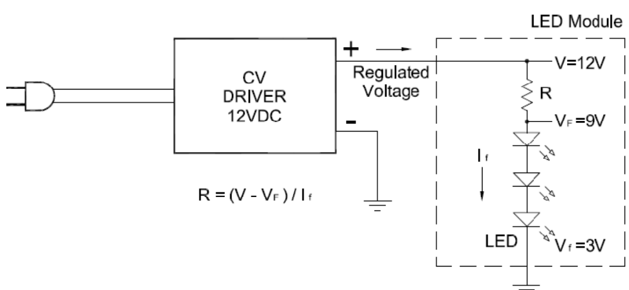


Fig. 4a- A Resistor Current Limiting circuit
$VF=V_{fLED1}+V_{fLED2}+V_{fLED3}$

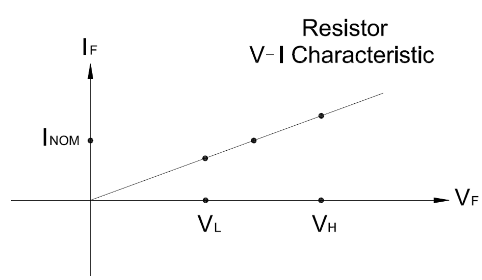


Fig. 4b - The V-I relationship where V_F is the supply voltage

In this method the resistor value R for a safe operating current of 120mA is determined as follows:
V=12Vdc (supply voltage)
$V_F=3xV_f=9V$
I_f=120mA **$R=(V-V_F)/I_f$** **R=(12-9) /.12=25Ω**

The 25Ω resistor must be rated properly to handle the dissipated power. Resistor power dissipation (P_R) is calculated as follows:

$P_R=(V-V_F) \times I_f$ **P_R=(12-9) x .12=.36W**

A commonly used.5W resistor is a good choice.

System Efficiency (E_{System}) is equal to driver efficiency (E_d) multiplied by Module Efficiency (E_m)[§]. In our example the system efficiency is calculated as follows:

System Power: $P_{System}=V \times I_f$ $P_{System}=12 \times .12=1.44W$ therefore,
Module Efficiency: $E_m=P_{System}/(P_R+P_{System})$ $E_m=1.44/(.36+1.44)=.8$ or, $E_m=80\%$
System Efficiency: $E_{System}=E_d \times E_m$ $E_{System}=.85 \times .8=.68$ or, $E_{System}=68\%$

Resistive Current Limiter systemsare very sensitive to power supply voltage fluctuation. A 5% voltage fluctuation in our example will translate to 20% change in $I_f$and about 18% fluctuation in light output.
$V_H=V+5\%$ $I_{f2}/I_{f1}=(V_H-V_f)/(V-V_f)$ $I_{f2}/I_{f1}=(12.6-9)/(12-9)=1.2$ or **+20% increase**
$V_L=V-5\%$ $I_{f2}/I_{f1}=(V_L-V_f)/(V-V_f)$ $I_{f2}/I_{f1}=(11.4-9)/(12-9)=0.8$ or **-20% decrease**
Despite its poor regulation, Resistor limiting CV approach is most popular in signage due to its lowest cost of material.

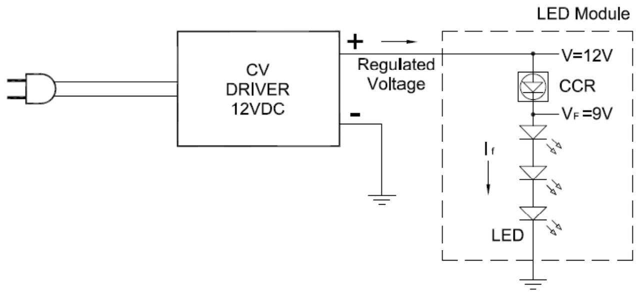
2-Active Linear Current Limiting- In this method the resistor of Fig. 4 is replaced by a Constant Current Regulator, CCR. The CCR is an active current control device, which has a set current over a much wider voltage range, (also referred to as Constant Current Diode, CCD, not to be mistaken with charge coupled device). This allows only the specific current to pass through the bank of LEDs (Fig. 5a, b).

For this method the CCR set current value (I_f) is selected for a safe operating current and is not adjustable. For our example: **V=12Vdc** $V_F=3xV_f=9V$ $I_f=120mA$

The CCR must be selected properly to easily handle the power dissipated by it. Power dissipation in the CCR is calculated as follows:
$P_{CCR}=(V-V_F) \times I_f$ $P_{CCR}=(12-9) \times .12=.36W$
A commonly used .5W or 1W CCR will be a good choice.

System Efficiency (E_{System}) is equal to driver efficiency (E_d) multiplied by Module Efficiency (E_m).[§] P_{CCR} is power consumed (lost) by the CCR. In our example the system efficiency is calculated as follows:
System Power: $P_{System}=V \times I_f$ $P_{System}=12 \times .12=1.44W$ therefore,
Module Efficiency: $E_m=P_{System}/(P_{CCR}+P_{System})$ $E_m=1.44/(.36+1.44)=.8$ or, $E_m=80\%$
System Efficiency: $E_{System}=E_d \times E_m$ $E_{System}=.85 \times .8=.68$ or, $E_{System}=68\%$

The CCR system has similar efficiency numbers to that of Resistor, but the advantage of CCR over Resistor is that as evident from its V-I curve the current I_f is regulated over much wider input voltage fluctuations (Fig. 5b). In general in a CCR system, which has a $\pm$5% current regulation band, a negligible 3.5% light output fluctuation is expected. This feature makes Constant Voltage CCR systems more desirable for light output uniformity when connecting multiple modules in series over long distances as voltage drops by longer wire length. This is more costly than the resistive approach shown above, but it offers some performance advantages.



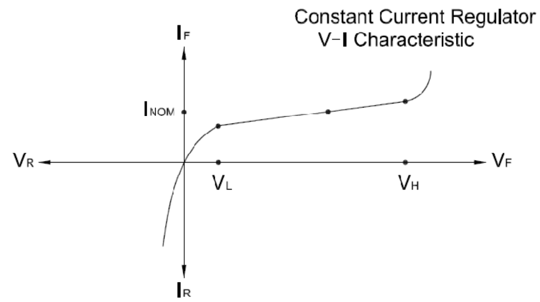


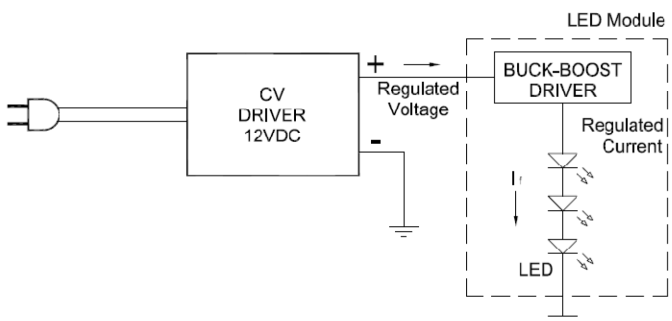
Fig. 5a- An Active Linear Current Limiting circuit. I_f is set by selecting a CCR with appropriate Forward Current

Fig. 5b- V-I relationship of a CCR where If varies slightly by a fluctuating supply voltage

3-Constant Current Buck-Boost Driver-In this method a second driver (Constant Current Buck-Boost) is designed onto the LED module to convert constant voltage from the main driver to a constant current source for the LEDs. The Buck-Boost driver is an active device that is similar in operation to the Constant Current driver explained above. It is designed to regulate well and to produce only one set current.

System efficiency is equal to combination of both drivers.[§] E_{bb} is the Buck-Boost Driver efficiency.
System Efficiency: **$E_{System}=E_d \times E_{bb}$** **$E_{System}=.85 \times .85=.56$** or, **$E_{System}=72\%$**

Due to higher efficiencies of both the main and the Buck-Boost drivers, this method is more efficient than other CV options. Of the various CV options discussed, Constant Current Buck-Boost Driver method provides the best light output control over long distance runs, and it is more efficient but due to its complexity and high component count, this method is the most costly for a CV system.



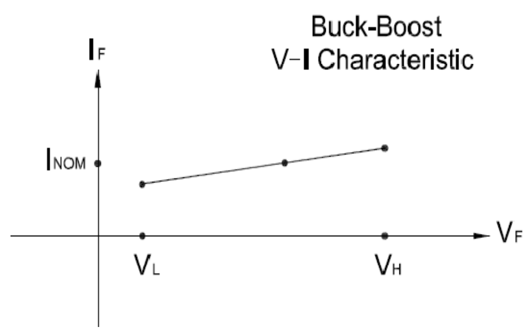


Fig. 6a- Constant Current Buck-Boost Driver circuit is set by design with a fixed Forward Current I_f

Fig. 6b- The V-I relationship where If varies unnoticeably by fluctuating supply voltage

Point of Use- Multiple CV modules may be connected in a parallel configuration powered by a single CV driver. In this case the total current of all modules must not exceed that of the driver. In the Fig.7 example, 3 of the modules of Fig. 4a are connected in parallel, requiring 3 x 120mA=360mA, so the driver must be capable of supplying 12 volts at a minimum current of 360mA.

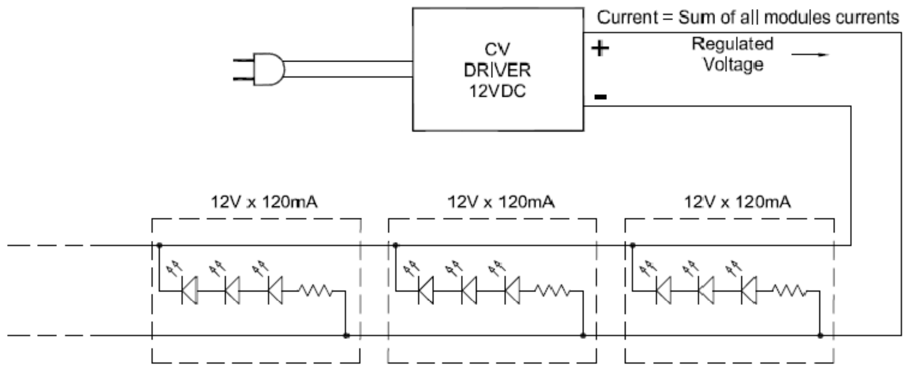


Fig. 7- A 12V CV driver-module set with 3 modules in parallel. Currents add up (3x120mA=360mA) but voltage remains at 12V. More modules may be added to the chain provided driver current allows it

Pros and Cons of CV Modules with Various Current Limiting

Pros: Any CV module can be matched with any CV driver that has the same output voltage.

Many modules can be parallel wired to the same driver providing ease of integration scalability.

For CCR and Buck-Boost limiters in a chain, LRD brightness is constant by distance from the driver over longer wire lengths.

Cons: CV systems are generally less efficient since the system efficiency is limited to the CV driver efficiency multiplied by the module efficiency; 50%-75% system efficiency range is common.

System cost is medium to high due to added components, with cost of Buck-Boost Driver type being the highest.

LED brightness diminishes as wire length increases for the Resistor system.

Summary

LEDs are “Current” controlled devices; however by employing a variety of current limiting techniques it is possible to produce reliable LED light by using CC or CV LED modules and driver systems. In designing an LED luminaire all aspects of various possible options need to be considered:

- Cost of components and assembly
- Reliability effect of component types and count in the system (MTBF)
- Efficiency (Energy Star), and resulting cooling requirements
- Scalability and ease of integration

Each system has inherent advantages and disadvantages. There is no one fits all. Table 1 summarizes pros and cons of each design option.

Table 1- Comparison between various LED systems

System	Construction	Driver & Eff.	Module & Eff. §	System Eff. §	Sys. Efficacy § (A=Highest)	System Cost (1=Best)	Characteristics
CC system	CC driver; No voltage drop on the module	CC driver 80-95%	Only LED on Module 100%	80-95%	A	1	Brightness is constant by distance from driver
CV system-1	CV driver; Resistive current limiter (linear control) on the module	CV driver 80-85%	Resistive current limiter on the module 60-80%	40-68%	C	2	brightness will drop by distance from driver
CV system-2	CV driver; Active linear current limiter on the module (diode/transistor)	CV driver 80-85%	Active linear current limiter on the module 60-80%	40-68%	C	3	Brightness drop by distance can be managed but to an extent
CV system-3	CV driver; Buck switch mode current limiter on the module	CV driver 80-85%	Buck driver on the module 75-90%	60-76%	B	4	Brightness is constant by distance but to an extent depending on driver quality

§- For the purpose of this paper we have neglected the electrical efficiency of LEDs because they are the "Productive" components in the system, which convert electricity to light. That conversion efficiency is referred to as Efficacy and is measured in units of Lumens per Watt (LPW).