Increase the Number of Series White LEDs with a "Constant Voltage" OVP Circuit

Introduction
A unique over-voltage protection (OVP) circuit is presented for use with the AAT1231, an inductive boost constant current white LED driver. The circuit allows transition from constant current to constant voltage at the OVP threshold, maintaining the programmed output voltage and current during abnormal OVP conditions. In addition, during closed-loop operation, the OVP "constant voltage" implementation allows seamless transition back to constant current mode when the abnormal condition(s) have been removed.

End-use display applications include main display backlighting and flash/torch mode lighting found in camera phones and digital still cameras. Moreover, increased numbers of series connected white LEDs are desired to support larger displays and increased lighting demands of next generation handheld devices.

The new OVP circuit eliminates the risk of LED flickering which occurs with OVP circuits when they cease to regulate during an OVP condition. This allows the designer to reduce the margin between the maximum and operating voltage on the switching devices. The reduced operating margin allows the designer to increase the number of series connected LEDs used for a given boost converter design.

Background
Inductive-boost LED drivers must generate a high DC output voltage to maintain conduction in a series connected string of white LEDs. A series configuration is desired because it maintains ideal current matching between LEDs. However, series connected LEDs operate at higher voltages than parallel LED strings. The peak operating voltage of a series connected string of LEDs is a function of the summed forward voltages of each LED in the string at the maximum operating forward current. The maximum voltage rating of the switching MOSFET and output rectifier of the source driver must be considered to ensure reliable operation.

An inductive boost topology provides a high output voltage necessary for conduction of the LED string, as shown in Figure 1. MOSFET (S1) and rectifier D1 (a Schottky diode) must be rated to withstand the maximum output voltage (V_{OUT}) which appears at the anode of the series LED string at the maximum LED current (i.e., maximum output load) which appears across S1 and D1 during alternate switching cycles.

Figure 1: Schematic of AAT1231 with OVP Threshold Set by R2, R3; R1 Determines LED Current.
As shown in Figure 1, the LED forward current ($I_{\text{LED}}$) is programmed by the AAT1231 device by adjusting the voltage at the FB1 pin in response to the CTL pin input. Digital clock data is applied to the CTL pin and decoded by AnalogicTech's patented S'\text{C}wire™ (Simple Serial Control™) interface into a voltage setting on the FB1 pin ($V_{\text{FB1}}$). Resistor R1 programs the forward current through the series LED string:

$$I_{\text{LED}} = \frac{V_{\text{FB1}}}{R1}$$

The maximum voltage seen at S1 occurs during the switching OFF-time, when S1 is OFF and rectifier D1 is ON:

$$V_{\text{MAX(OFF)}} = V_{\text{OUT}} + V_F$$
$$= (N \cdot V_{F(\text{LED})} + V_{\text{FB1}}) + V_F$$

Where:

$N$ = Number of series white LEDs
$V_{F(\text{LED})}$ = LED forward voltage
$V_{\text{FB1}}$ = Voltage on the AAT1231 feedback pin
$V_F$ = Rectifying diode forward voltage

Maximum D1 reverse voltage occurs during the switching ON-time, when S1 is ON and rectifier D1 is OFF:

$$V_{R\text{-MAX(ON)}} = V_{\text{OUT}}$$

At room temperature, $V_{F(\text{LED})}$ can exhibit as much as +15% unit-to-unit tolerance at a given forward current. Additional tolerances due to operating temperature and current may also apply.

**Why Over-Voltage Protection?**

Over-voltage protection (OVP) is necessary to protect switch S1 (internal to the AAT1231) and rectifier D1 from excessive voltage ($V_{DS\text{-MAX(OFF)}}$, $V_{R\text{-MAX(ON)}}$) should abnormal conditions occur. Possible abnormal conditions include:

1. Open-loop fault (single point component failure)
2. Closed-loop tolerance build-up (high $V_{F(\text{LED})}$ tolerance build-up)

Typical OVP prevents damage during open-loop conditions by power cycling or latching-off the boost converter. This prevents over-voltage damage but fails to maintain DC current in the LED string, making the traditional OVP events unacceptable under closed-loop operating conditions.
Closed loop OVP may occur in extreme cases, when $V_{F(\text{LED})}$ tolerance build-up and/or operation at low temperatures is considered. As mentioned previously, $V_{F(\text{LED})}$ unit-to-unit variation can be as much as $+15\%$ (at room temperature):

$$V_{\text{OUT(MAX)}} = (N \cdot V_{\text{FLED(MAX)}} + V_{\text{FB1(MAX)}})$$

To ensure that OVP flicker is not activated during normal, closed-loop conditions, the system designer must include adequate operating voltage margin ($V_{\text{MARGIN}}$). The OVP threshold is programmed by an external resistor divider network to ensure safe voltage levels under all conditions:

$$V_{\text{OVPMIN}} = V_{\text{OUT(MAX)}} + V_{\text{MARGIN}}$$
$$= (N \cdot V_{\text{FLED(MAX)}} + V_{\text{FB1(MAX)}}) + V_{\text{MARGIN}}$$

**OVP with Constant Voltage Control**

OVP with constant voltage control maintains the programmed output voltage during abnormal operating conditions. Protection is guaranteed under an open-loop condition due to component failure or a closed-loop over voltage event due to excessive series LED string forward voltage $V_{F(\text{LED})}$. The OVP programming resistors set the maximum OVP threshold to ensure that the maximum voltage rating of the boost converter is not exceeded.

Consider the case where series LEDs exhibit an unusually high forward voltage ($V_{F(\text{LED})}$) and/or operation at low temperature is required. When the rising OVP threshold is exceeded, boost converter switching is stopped and the output voltage decays. Switching automatically restarts when the output drops below the lower OVP hysteresis voltage (100mV, typical) and, as a result, the output voltage increases. The cycle repeats, maintaining an average DC output voltage proportional to the average of the rising and falling OVP levels (multiplied by the resistor divider scaling factor). The high operating frequency of the boost converter and small output voltage ripple ensure a constant output DC current and negligible flicker in the LED string(s).

During an OVP constant voltage event, the LED current may be reduced. During closed-loop operation, while OVP is active, the maximum LED current programming error ($\Delta I_{\text{LED}}$) is proportional to the voltage error across an individual LED ($\Delta V_{\text{LED}}$).

$$\Delta V_{\text{LED}} = \frac{(N \cdot V_{\text{FLED(MAX)}} - V_{\text{OVPMIN}} - V_{\text{FB1}})}{N}$$

Figure 2 illustrates the output LED current and voltage for the AAT1231 boost constant current driver in closed-loop operation. Two voltage curves are shown which represent minimum and maximum $V_{F(\text{LED})}$ characteristics. A high $V_{F(\text{LED})}$ yields increased output voltage. OVP with constant voltage control allows the design to operate above the OVP threshold with negligible reduction in output LED current.
Conclusion

A unique over-voltage protection (OVP) circuit is presented which allows transition from constant current to constant voltage operation at a programmed OVP threshold. The OVP circuit maintains safe operating voltages under open-loop (single point failure) and closed-loop (positive $V_{f(LED)}$, tolerance build-up) conditions. The OVP closed-loop constant voltage mode represents an additional operating area which is unavailable using traditional OVP circuits. The system designer can reduce operating voltage margin and potentially increase the number of LEDs in the series string without the risk of LED flicker or power cycling. The OVP circuit will transition back to constant current mode operation when the abnormal condition is removed.

End-use applications include main display backlighting and flash/torch mode lighting found in camera phones, digital still cameras, and other portable consumer electronic products. Using the AAT1231’s OVP feature in a constant-voltage implementation presented here addresses the increased backlighting demands of the larger displays required in next-generation hand-held and portable products.