AAT2404

Voltage-Variable Current Sourcing Boost Controller For LED Lighting Applications

General Description

The AAT2404 is a highly integrated high-efficiency variable voltage current sourcing boost controller for white LED backlight applications intended for use in large size LCD panels and LCD TVs. To accommodate various LED backlighting configurations in both direct and edge lighting applications, the device uses a high voltage external power MOSFET. The AAT2404 contains an integrated current sense architecture eliminating the need for an expensive low resistance/high accuracy sense resistor. The device operates ideally from a regulated 12V or 24V DC power supply, but can also operate over a 10.8V to 28V range.

The AAT2404 provides an output voltage up to 100V regulated by the CSFB pin provided by the ICs in Skyworks' family of white LED drivers for TV applications. The CSFB pin is an analog voltage representing the LED string with the highest voltage requirement. Regulating to this voltage allows for a wide range of LED characteristics, while maintaining the lowest possible power dissipation. The CSFB regulation point can be set by adjusting a resistor to ground from the RSET pin.

The boost switching frequency is nominally 400kHz to allow for optimum efficiency with the smallest external filter. However, the device switching frequency may be adjusted with an external resistor to optimize system performance. Current mode control provides fast response to line and load transients.

Thermal protection circuitry shuts down the boost converter in the event of an over-temperature condition.

The AAT2404 is available in the Pb-free, thermally enhanced 24-pin 3 x 4mm TQFN package.

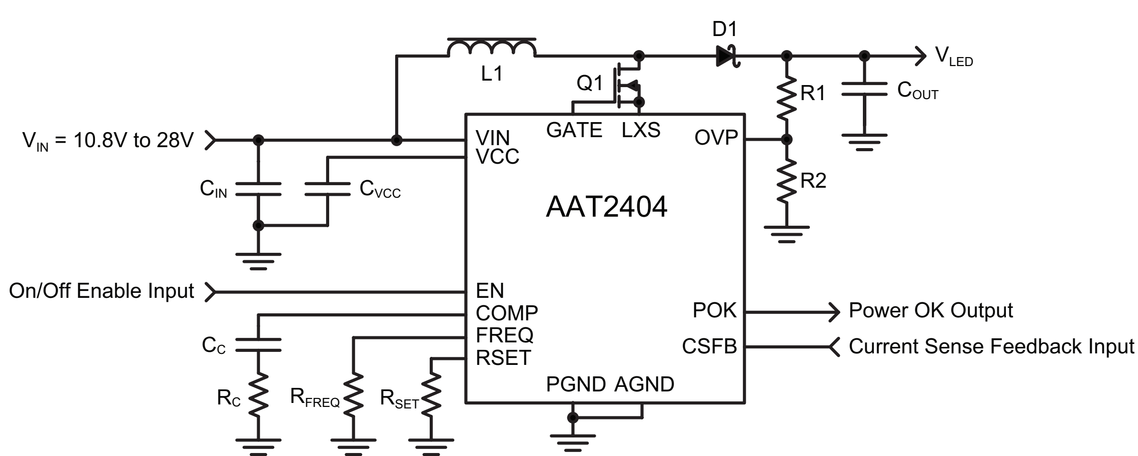
Features

- V_{IN} Range: 10.8V – 28.0V
- Maximum V_{LED}: 100V
- Up to 95% Boost Conversion Efficiency
- Integrated Current Sense Eliminates Need for Ballast Resistors
- Switching Frequency Options
  - 400KHz Nominal
  - Adjustable Range from 100kHz to 800kHz
- Adjustable Regulation Voltage
  - Analog Input from LED Driver
  - User Adjustable for Fixed Output
- Integrated Low Impedance Gate Drive = V_{CC}
- Flexible Current Sense Feedback Control
- Power OK Output
- Integrated Over-Voltage Protection
- Soft-Start to Minimize Inrush Current
- TQFN34-24 Low Profile Package
- -40°C to +85°C Temperature Range

Applications

- Large Size LCD TV, Panels
- LCD Monitors
- Video Walls
- White LED Backlighting

Typical Application

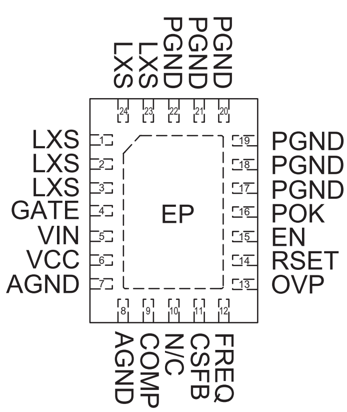


Pin Descriptions

Pin #	Symbol	Function	Description
1, 2, 3, 23, 24	LXS	I	Boost converter current sense node. Connect to the source terminal of the external low resistance power MOSFET to this pin.
4	GATE	O	Output drive pin. Connect directly to the gate terminal of the external low resistance power MOSFET. The gate voltage range is from 0V to V_{CC}
5	VIN	I	Input power supply.
6	VCC	I/O	Internally regulated power supply. Decouple with 2.2μF or greater value capacitor between this pin and AGND.
7, 8	AGND	GND	Analog ground.
9	COMP	I	Boost converter compensation. Connect external resistor and capacitor to this pin and AGND.
10	NC		Not connected.
11	CSFB	I	Current sink feedback. When used with compatible Skyworks LED driver devices[1], connect the driver CSFBO output directly to this pin for the current sink feedback from current sink device.
12	FREQ	O	Boost converter PWM switching frequency adjust pin. Connect a R_{FREQ} resistor between this pin and AGND to set the switching frequency.
13	OVP	I	Over-voltage protection. Connect a resistive divider between V_{LED}, this pin, and ground.
14	RSET	O	Current sink regulation voltage set resistor. Connect the R_{SET} resistor between this pin and AGND.
15	EN	I	Logic High enable pin. Apply a logic high voltage or connect to VIN to enable the device. Use a 10kΩ resistor between this pin and AGND to for a logic pull-down to shut the device off when an enable signal is not applied.
16	POK	O	Open drain output. Connect to LED cathode with the anode connected via a resistor to VCC or drive an active low logic signal to a system controller. If not used, leave open / not connected.
17, 18, 19, 20, 21, 22	PGND	GND	Power ground.
EP	EP	GND	Exposed paddle. Connect to PCB GND plane. PCB paddle heat sinking should maintain acceptable junction temperature.

Pin Configuration

TQFN34-24
(Top View)



1. Compatible Skyworks LED backlight driver products include the AAT2401, AAT2402 and AAT2403.

Absolute Maximum Ratings[1]

Symbol	Description	Value	Units
$V_{IN,EN}$	Input Voltage, EN to GND	-0.3 to 32	V
V_{CC}	Low Voltage Pin to GND	-0.3 to 6.0	
GATE, LXS, POK, OVP, COMP, RSET, FREQ, CSFB	GATE, LXS, POK, OVP, COMP, RSET, FREQ, CSFB Voltage to GND	-0.3 to V_{CC} + 0.3	
T_J	Maximum Junction Operating Temperature	-40 to +150	°C
T_{LEAD}	Maximum Soldering Temperature (at leads, 10 sec.)	300	

Thermal Information[2]

Symbol	Description	Value	Units
θ_{JA}	Thermal Resistance[3]	50	°C/W
P_D	Maximum Power Dissipation	2.3	W
T_A	Operating Temperature Range	-40 to 85	°C

1. Stresses above those listed in Absolute Maximum Ratings may cause permanent damage to the device. Functional operation at conditions other than the operating conditions specified is not implied. Only one Absolute Maximum Rating should be applied at any one time.
2. Mounted on an FR4 board.
3. Derate 20mW/°C above 25°C.

Electrical Characteristics[1]

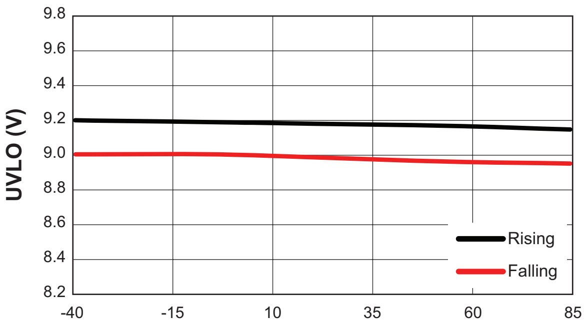
V_{IN} = 24V; C_{IN} = 4.7µF, C_{OUT} = 4.7µF; C_{VCC} = 2.2µF; L_1 = 10µH; R_{SET} =10.2kΩ; T_A = -40°C to 85°C unless otherwise noted. Typical values are at T_A = 25°C.

Symbol	Description	Conditions	Min	Typ	Max	Units
Power Supply, Current Sinks						
V_{IN}	Input Voltage Range		10.8		28	V
V_{CC}	Linear Regulator Output Voltage	0mA < I_{LOAD} < 15mA		5.0		V
V_{UVLO}	Under Voltage Threshold	V_{IN} Rising			10	V
		Hysteresis		200		mV
		V_{IN} Falling	8.5			V
V_{LED}	Output Voltage Range	V_{IN} = 10.8V to 28.0V	V_{IN} + 3V			V
I_Q	Quiescent Current	Not switching		1		mA
I_{SD}	VIN Pin Shutdown Current	EN = Logic Low		10		µA
V_{OVP}	Over-Voltage Threshold	V_{LED} Rising	1.1	1.2	1.3	V
	Over-Voltage Hysteresis	V_{LED} Falling		100		mV
R_{SENSE}	Sense Device ON Resistance			60		mΩ
I_{LIMIT}	Low Side Switch Current Limit			10		A
F_{OSC}	Oscillator Frequency	R_{FREQ} = 10kΩ	320	400	480	kHz
T_{SS}	Soft-Start	V_{LED} = 35V		1.5		ms
D	Duty Cycle[2]	R_{FREQ} = 10kΩ		80		%
Gate Drive						
R_{DS_P}	Driver High Side ON Resistance	V_{CC} = 5V		2		Ω
R_{DS_N}	Driver Low Side ON Resistance	V_{CC} = 5V		1		
t_R	Gate Rise Time	V_{CC} = 5V, C_{LOAD} = 0.5nF		10		ns
t_F	Gate Fall Time	V_{CC} = 5V, C_{LOAD} = 0.5nF		10		ns
Logic Level Inputs: EN						
$V_{I(L)}$	Input Logic Threshold Low				0.4	V
$V_{I(H)}$	Input Logic Threshold High		2.5			V
I_{EN}	Input Enable Leakage Currrent				2	µA
Logic Level Outputs: POK						
$V_{POK(LOW)}$	POK Logic Output Low	I_{SINK} = -1mA			0.4	V
I_{SINK}	POK Logic High Leakage	V_{POK} = 5.5V			1	µA
Thermal Protection						
$T_{J\ (SD)}$	T_J Thermal Shutdown Threshold			140		°C
$T_{J\ (HYS)}$	T_J Thermal Shutdown Hysteresis			15		

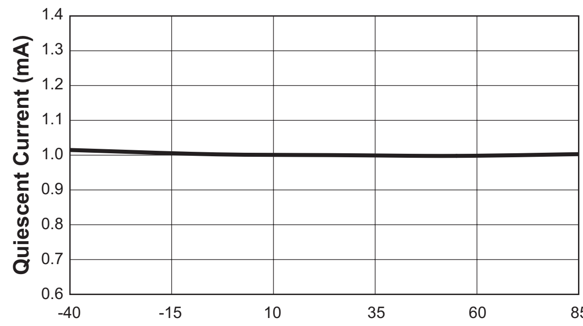
1. The AAT2404 is guaranteed to meet performance specifications over the -40°C to +85°C operating temperature range and is assured by design, characterization, and correlation with statistical process controls.
2. The boosted output voltage, V_{LED}, cannot exceed 100V.

Typical Characteristics

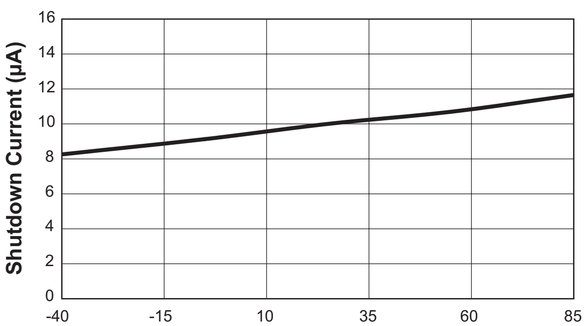
UVLO vs. Temperature



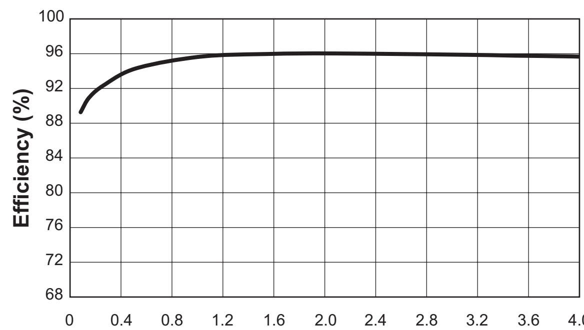
Quiescent Current vs. Temperature
(V_{IN} = 24V; V_{EN} = V_{IN}; Non-switching)



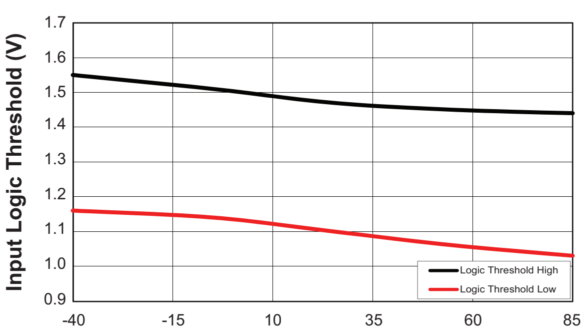
Shutdown Current vs. Temperature
(V_{IN} = 24V; V_{EN} = GND)



Efficiency vs. Load Current
(V_{IN} = 24V; V_{LED} = 31V; C_{OUT} = 20µF; L = 10µH)

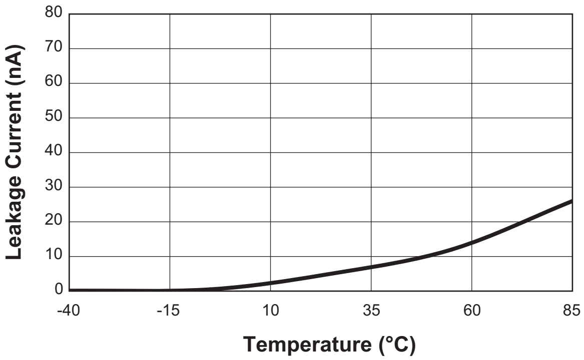


Input Logic Threshold vs. Temperature
(V_{IN} = 24V)

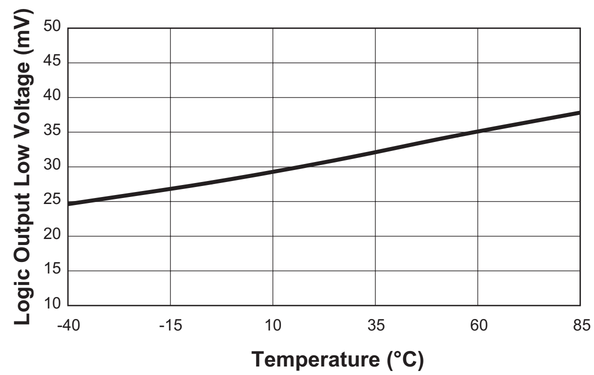


Typical Characteristics

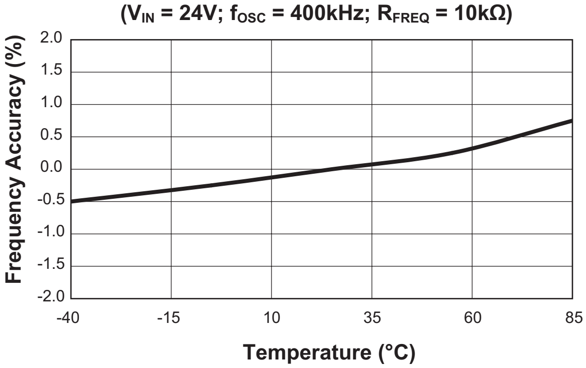
POK Logic High Leakage vs. Temperature
(V_{IN} = 24V; V_{POK} = 5.5V)



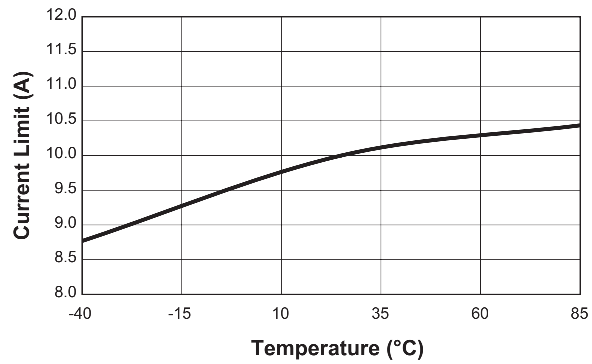
POK Logic Output Low vs. Temperature
(V_{IN} = 24V; I_{POK} = -1mA)



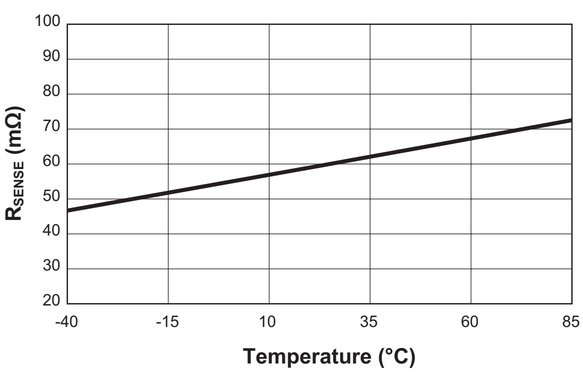
Oscillator Frequency Accuracy vs. Temperature
(V_{IN} = 24V; f_{OSC} = 400kHz; R_{FREQ} = 10kΩ)



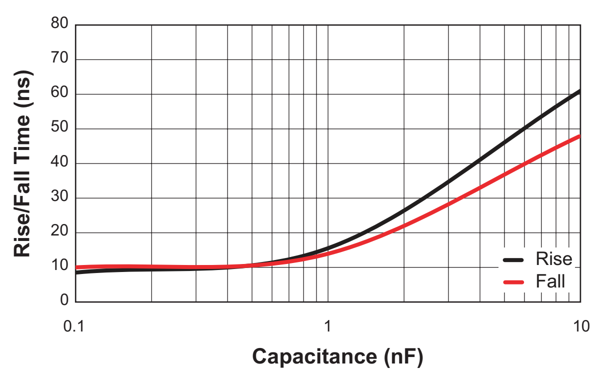
Current Limit vs. Temperature
(V_{IN} = 24V)



Sense Device On Resistance vs. Temperature

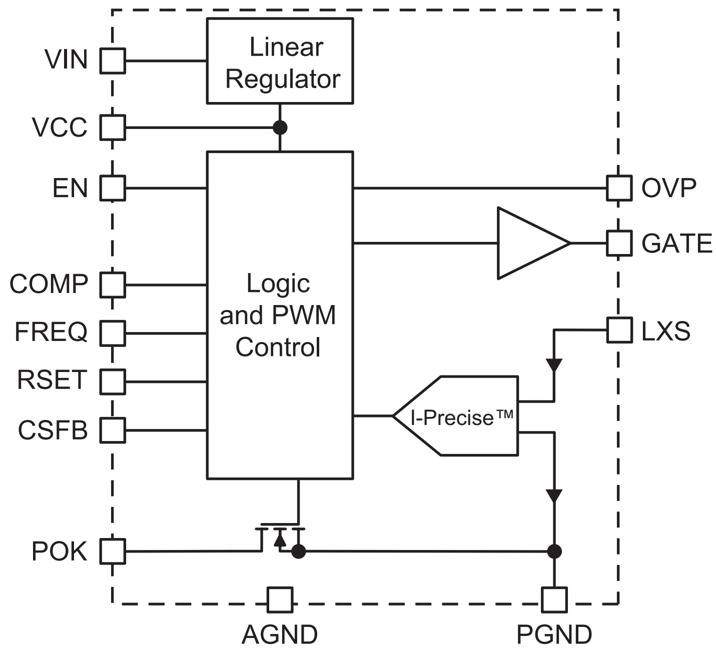


Gate Rise and Fall Time vs. C_{LOAD}
(V_{IN} = 24V; V_{CC} = 5V)



Voltage-Variable Current Sourcing Boost Controller For LED Lighting Applications

Functional Block Diagram



Functional Description

The AAT2404 is a high voltage DC-DC boost converter that functions as a voltage variable current source that is designed to complement Skyworks' family of white LED drivers for TV applications

Operating from a 10.8V to 28V input supply range, the AAT2404 can supply a compliance voltage up to 100V with the output power limited only by the size and selection of the external switching MOSFET, inductor and schottky diode. Input voltage sources common to LCD monitors and TV display panels are 12V or 24V with a maximum effective switching duty cycle of 80%.

The AAT2404 uses a unique internal current scheme, and relies on a current sense feedback loop (CSFB) integrated into the AAT2401/02S/03 LED driver ICs which eliminates the need for low resistance, 1% tolerance current sense resistors for each LED backlight string. The CSFB function is an analog voltage feedback system that represents the LED string with the highest voltage requirement. Regulating to this voltage allows for a wide range of LED characteristics, while maintaining the lowest possible power dissipation for the system. The CSFB regulation voltage point can be set by adjusting an external resistor to ground from the RSET pin.

The AAT2404 provides a low gate impedance driver to minimize the switching losses of the external boost power MOSFET and can attain boost conversion efficiencies up to 95%. The boost switching frequency is nominally 400kHz to allow for optimum efficiency with the smallest external filter. Alternatively, the device switching frequency may be adjusted over a 100kHz to 800kHz range by an external resistor if required by a specific application.

For reliability and protection of the application system, the AAT2404 has a thermal protection circuit to shut down the boost converter in the event of an over-temperature condition. An output over voltage protection circuit (OVP) constantly monitors the boost output voltage and will terminate the boost switching cycle if the output exceeds a user set threshold.

Input Supply and Control Loop

The AAT2404 has specially designed input stages to permit operation and control over a 10.8V to 28V input range. This device is intended to function as a voltage variable current source to drive large strings of backlight LEDs. The system current limit is based on the programming of the downstream LED controller constant current sinks. The current sink feedback to the AAT2404 maintains a compliance voltage to support the varying demands based on the LED combined forward voltage at any given forward current setting.

The AAT2404 has the benefit of current mode control with a simple voltage feedback loop providing exceptional stability and fast response with minimal design effort. The device modulates the external power MOSFET switching current to maintain the programmed feedback voltage that is user adjustable via the RSET resistor. The switching cycle initiates when the N-channel MOSFET is turned ON and current ramps up in the inductor. The ON interval is terminated when the inductor current reaches the programmed peak level. During the OFF interval, the input current decays until a lower threshold, or zero inductor current, is reached. The lower current is equal to the peak current minus a preset hysteresis threshold, which determines the inductor ripple current. The peak current is adjusted by the controller until the output voltage requirement of the LED array is met as determined by the voltage on the CSFB input pin.

Operating frequency varies with changes in the input voltage, output voltage, and inductor size. Once the boost converter has reached continuous mode, further increases in the output current will not significantly change the operating frequency.

Control Loop Compensation

The COMP pin is the output of the transconductance error amplifier. The AAT2404 is a current mode boost controller and as such has eliminated the double pole of the LC filter. The magnitude of the feedback error signal determines the average input current to the AAT2404; the internal control circuit implements a programmed current source connected to the output capacitor and load impedance. Regulator stability is achieved with a simple RC compensation network from the COMP pin to ground. If the ESR of the output capacitor is high, then an additional capacitor in parallel with the RC network may be needed.

Current Sink Feedback (CSFB) and RSET

The AAT2404 utilizes a current sink feedback (CSFB) function that directly interfaces to Skyworks LED controllers such as the AAT2401, AAT2402S and AAT2403. When used with these devices, their integrated CSFBO output can be connected directly to the AAT2404 CSFB pin. The voltage level of this feedback system represents the proper regulation point for the LED array to support a programmed LED drive current. The range of the CSFB signal should be from 0.5V to 2.5V under normal operating conditions.

The feedback voltage threshold is user adjustable by programming the R_{SET} resistor, simplifying integration with other Skyworks's devices. The feedback threshold voltage for the AAT2404 should be greater than the current sink dropout voltage to prevent I_{LED} from going out of regulation. However if the feedback voltage threshold is much higher than the dropout voltage, the V_{LED} voltage will be higher than the optimum voltage required to drive the white LED strings. This will result in unwanted power being dissipated by the LED driver. Set the feedback voltage threshold between 10% and 20% higher than the dropout voltage to maintain current regulation and avoid excessive power dissipation.

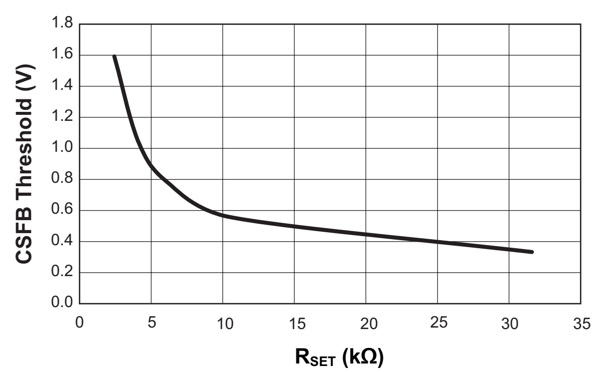


Figure 1: CSFB Threshold vs. R_{SET} (V_{IN} = 24V, F_{OSC} = 200kHz).

Voltage-Variable Current Sourcing Boost Controller For LED Lighting Applications

Maximum Output Voltage Compliance

When using the AAT2404 in a given application, one must first determine what the maximum combined LED string voltage will be at the specified maximum forward current. The maximum practical operating duty cycle for the DC-DC boost function is approximately 80%.

The maximum output voltage can be approximated using Equation 1:

$$\textbf{Eq. 1: } V_{LED} = \frac{V_{IN}}{1 - D}$$

Where D = DC-DC boost switching duty cycle.

However, the maximum output voltage should not exceed 100V.

Internal Linear Voltage Regulator

The AAT2404 has an internal linear regulator to produce 5V from the VIN high voltage input for internal logic, clock, and control functions. The regulator output is connected to the VCC pin and should be bypassed with a 2.2μF or larger ceramic capacitor. The 5V may be used as a logic pull-up reference termination for all AAT2404 logic functions such as a pull up for the open drain power OK (POK) function. This output is not intended to support external loads from circuits other than low current logic terminations.

IC Enable and Soft Start

An enable pin is provided as a master on/off function that may be toggled by an external system controller or connected directly to VIN. This is a logic active high function. If the IC enable is not needed, connect the EN pin to VCC to turn the AAT2404 on. The slew rate limited turn-on is guaranteed by the built-in soft-start circuitry. Soft start eliminates output current overshoot across the full input voltage range and all load conditions. After the soft start sequence has terminated, the initial output voltage is determined by the level sensed on the CSFB pin.

Boost Converter Switching Frequency

The AAT2404 is designed to operate over a wide input to output voltage range with a nominal 400kHz switching frequency. However, if a specific system or application demands a different operating switching frequency, the frequency can be user adjusted by changing the resistor value between the FREQ pin and ground. To set a recommend 400kHz switching frequency, the nominal value R_{FREQ} value is 10kΩ. Refer to Figure 2 for resistor values to program a specific switching frequency.

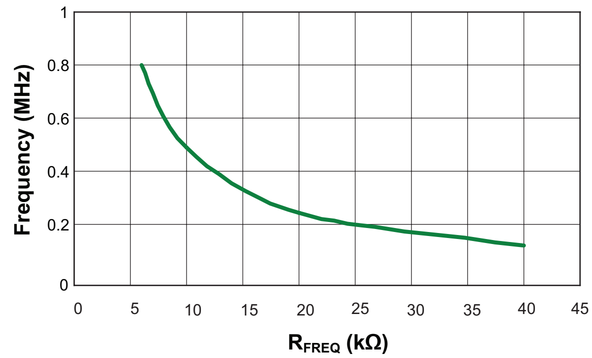


Figure 2: AAT2404 DC_DC Boost Switching Frequency vs. R_{FREQ} Resistor Value.

OVP

The over-voltage protection (OVP) circuit is provided to shut down the boost control switching to the external N-channel MOSFET if the output voltage exceeds a user preset level, which can occur if the load circuit becomes disconnected (open). The OVP pin input threshold is 1.2V and the OVP shutdown voltage should be selected so that the circuit is active within a reasonable margin above the normal output operation voltage. To program a desired OVP output limit level, place a resistor divider between the voltage output node, the OVP pin, and ground. Set the OVP voltage using Equation 2:

$$\textbf{Eq. 2: } R1 = R2\left(\left[\frac{V_{OUTPUT\ PROTECTION}}{V_{OVP}}\right] - 1\right)$$

Where:

V_{OVP} = OVP threshold = 1.2V
$V_{OUTPUT\ PROTECTION}$ = Desired output protection voltage level

R2 should typically be set to 12.1kΩ (Nominal range for R2 should be between 10kΩ and 47kΩ). The maximum OVP is 120V.

Thermal Protect Shutdown

If an operating condition causes excess power dissipation in the AAT2404, the device will shut down when the die temperature exceeds 140°C. When the die cools or when the source of the over-temperature condition is removed, the AAT2404 will automatically restart. There is 15°C of shutdown restart hysteresis.

Power OK Flag Output

A power OK (POK) flag is provided to inform the system when the output supply voltage is turned on and has reached 80% regulation. The POK output is an open drain N-channel MOSFET switch connected to ground internally. A 10KΩ or greater value pull-up resistor should be connected between the POK pin and VCC. The POK flag can function as an active low logic signal that can be used to alert system logic or as an enable signal to a downstream load circuit to sequence the load power-on after the boost supply is operating.

Application Information

The AAT2404 is a highly integrated high-efficiency variable voltage current sourcing boost controller and like all boost controllers care must be taken in the selection of external components during the design stage to ensure a stable and reliable system. The design is an iterative process since design parameters are mutually dependant. As an example of this iterative process please refer to the step-by-step design example application note.

DC-DC Boost Duty Cycle Calculation

In order to correctly determine the characteristics for external component selection, the switching duty cycle for the boost converter function should be calculated. If the input voltage to the AAT2404 is constant, then there is only one maximum duty cycle condition to be concerned with (Equation 3). In the case of varied input supply, the minimum, maximum, and nominal duty cycle should be calculated (Equations 3, 4, and 5) and the use of the maximum value should be carried forward for the selection of the inductor, N-channel MOSFET, and reverse blocking diode.

Eq. 3: $$D_{NOM} = \frac{V_{LED} - V_{IN(NOM)} + V_D}{V_{LED} + V_D}$$

Eq. 4: $$D_{MIN} = \frac{V_{LED} - V_{IN(MAX)} + V_D}{V_{LED} + V_D}$$

Eq. 5: $$D_{MAX} = \frac{V_{LED} - V_{IN(MIN)} + V_D}{V_{LED} + V_D}$$

Where:

D_{MIN} = Minimum boost switching duty cycle
D_{MAX} = Maximum boost switching duty cycle (must be ≤ 80%)
D_{NOM} = nominal boost switching duty cycle
$V_{IN[MAX]}$ = Maximum input supply voltage for the application
$V_{IN[MIN]}$ = Minimum input supply voltage for the application
V_{LED} = Voltage output of the boost regulator (estimate the maximum summed V_F for the LED string for the backlighting application)
V_D = Reverse blocking diode forward voltage. A Schottky diode is recommended for this application due to their low forward voltage characteristic. The V_F of a Schottky diode is typically between 0.5V and 0.7V.

Selecting the Switching Frequency

Selecting the optimal switching frequency is an iterative process since component and electrical parameters are all interrelated. For example, to reduce the inductor value and hence its size a higher switching frequency is desired. However, too high of a switching frequency may cause the switching losses in the external N-channel boost MOSFET to become dominant and exceed the power dissipation. A good starting point for the switching frequency is between 200kHz and 400kHZ. To set the switching frequency, please refer to the Boost Converter Switching Frequency section of this product datasheet.

Selecting the Boost Inductor

The first parameter to be considered in the selection of the boost inductor is the inductance value. In a fixed-frequency boost converter like the AAT2404, this value is based on the desired peak-to-peak ripple current ΔI_L, which flows in the inductor along with the average or DC inductor current I_L. In continuous conduction mode (CCM) I_L is greater than the current output of the boost regulator, I_{LED}. Taking into account the conservation of power and neglecting efficiency losses, the two currents are related by the following:

Conservation of power:

Eq. 6: $$V_{IN} \cdot I_L = V_{LED} \cdot I_{LED}$$

Eq. 7: $$V_{LED} = \frac{V_{IN}}{(1 - D)}$$

Rearranging for I_L:

Eq. 8: $$I_L = \frac{V_{LED} \cdot I_{LED}}{V_{IN}}$$

Substituting V_{IN} for V_{LED}:

Eq. 9: $$I_L = \frac{\frac{V_{IN}}{(1 - D)} \cdot I_{LED}}{V_{IN}}$$

Eq. 10: $$I_L = \frac{I_{LED}}{(1 - D)}$$

Where:

V_{IN} = Input supply voltage
V_{LED} = Voltage output of the boost regulator
I_L = Average inductor current or input supply current
I_{LED} = Current output of the boost regulator
D = Boost switching duty cycle

The inductance value chosen is a tradeoff between size and cost. Larger inductance means lower input ripple current, however because the inductor is connected to the output during the off-time, there is a limit to the reduction in output ripple voltage. Lower inductance results in smaller, less expensive magnetics. An inductance that gives a ripple current of 30% of I_L is a good starting point for a CCM boost converter:

Eq. 11: $\Delta i_{L(MAX)} \approx 0.3 \cdot \frac{I_{LED}}{1 - D}$

Where:

$\Delta i_{L(MAX)}$ = Maximum desired inductor peak to peak current ripple
I_{LED} = Current output of the boost regulator
D = Boost switching duty cycle

Minimum inductance should be calculated at the extremes of input voltage to find the operating condition with the highest requirement. Depending on the amount the input voltage is boosted, the duty cycle term (D) can become the dominant term. The minimum inductor value can be established by one of the following equations, whichever produces the larger minimum inductor value:

Eq. 12: $L_{MIN} = \frac{V_{IN(MAX)}}{\Delta i_{L(MAX)}} \cdot D_{MIN} \cdot \frac{1}{f_{SW}}$

Eq. 13: $L_{MIN} = \frac{V_{IN(MIN)}}{\Delta i_{L(MAX)}} \cdot D_{MAX} \cdot \frac{1}{f_{SW}}$

Where:

L_{MIN} = Minimum inductance
$V_{IN(MAX)}$ = Maximum input supply voltage
$V_{IN(MIN)}$ = Minimum input supply voltage
$\Delta i_{L(MAX)}$ = Maximum inductor peak to peak current ripple
D_{MIN} = Minimum boost switching duty cycle
D_{MAX} = Maximum boost switching duty cycle
f_{SW} = Switching frequency

Based on the inductor value calculation, the next higher standard value inductor should be used.

The second parameter that should be taken into consideration when selecting the boost inductor is the peak current capability. This is the level above which the inductor will saturate and the inductance can drop severely, resulting in a higher peak current that may overheat the inductor and/or push the AAT2404 into current limit. In a boost converter, peak inductor current, I_{PK}, is equal to the maximum average inductor current plus one half of the ripple current. First, the ripple current, Δi_L, must be determined under the conditions that give maximum average inductor current:

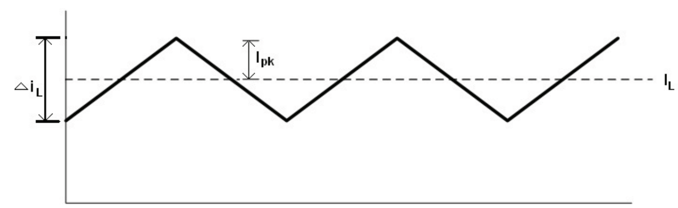


Figure 3: CCM Inductor Current.

Eq. 14: $\Delta i_L = \frac{V_{IN(MIN)}}{L} \cdot D_{MAX} \cdot \frac{1}{f_{SW}}$

Eq. 15: $\Delta i_L = \frac{V_{IN(MAX)}}{L} \cdot D_{MIN} \cdot \frac{1}{f_{SW}}$

Eq. 16: $I_{L(PK)} = I_L + \frac{\Delta i_L}{2}$

Where:

Δi_L = Nominal ripple current in the inductor
$V_{IN(MIN)}$ = Minimum input voltage
L = Inductance
D = Boost switching duty cycle
f_{SW} = Switching frequency
$I_{L(PK)}$ = Peak inductor current
I_L = Average inductor current

I_{PK} should be less than the saturation current specification of the selected inductor.

The final parameter of an inductor to consider is the DC resistance (DCR), which contributes to the power loss of the inductor and degrades the boost converter efficiency and increases the inductor's operating temperature.

Eq. 17: $P_{LOSS(L)} = I^2_{RMS} \cdot DCR$

Where:

Eq. 18: $I_{RMS} = \sqrt{(I_L)^2 + \left(\frac{1}{12}\Delta i_L\right)^2}$

is the RMS current in the inductor for continuous conduction mode operation.

Selecting the Schottky Diode

A low forward voltage drop Schottky diode is used as a rectifier diode to reduce its power dissipation and improve efficiency.

The average current through diode is the average load current I_{LED}, and the peak current through the diode is the peak current through the inductor I_{PK}. The diode should be rated to handle more than its peak current.

Eq. 19: $$I_{D(PK)} = I_{L(PK)} = I_L + \frac{\Delta i_L}{2}$$

Where:

$I_{D(PK)}$ = Peak diode current
$I_{L(PK)}$ = Peak inductor current
I_L = Average inductor current
Δi_L = Nominal ripple current in the inductor

The peak reverse voltage for the boost converter is equal to the regulator output voltage. The diode must be capable of handling this voltage. Using 80% derating on V_{LED} for ringing on the switch node, the rectifier diode minimum reverse breakdown voltage is:

Eq. 20: $$V_{BRR(MIN)} \geq \frac{V_{LED}}{0.8}$$

Where:

$V_{BRR(MIN)}$ = Minimum voltage breakdown of the Schottky diode
V_{LED} = Voltage output of the boost regulator

To assure the rectifier diode is rated for the power dissipation requirement for a given application, the Schottky diode power dissipation can be estimated.

The switching period is divided between ON and OFF time intervals:

Eq. 21: $$\frac{1}{F_S} = T_{ON} + T_{OFF} = D + D'$$

During the ON time, the N-channel power MOSFET is conducting and storing energy in the boost inductor. During the OFF time, the N-channel power MOSFET is not conducting. Stored energy is transferred from the input battery and boost inductor to the output load through the output diode. Duty cycle is defined as the ON time divided by the total switching interval:

Eq. 22: $$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} = T_{ON} \cdot F_S$$

The maximum duty cycle can be estimated from the relationship for a continuous mode boost converter. Maximum duty cycle (D_{MAX}) is the duty cycle at minimum input voltage ($V_{IN(MIN)}$):

Eq. 23: $$D_{MAX} = \frac{V_{LED} - V_{IN(MIN)}}{V_{LED}}$$

The average diode current during the OFF time can be estimated:

Eq. 24: $$I_{AVG(OFF)} = \frac{I_{LED}}{1 - D_{MAX}}$$

The V_F of the Schottky diode can be estimated from the average current during the off time. The average diode current is equal to the output current:

Eq. 25: $$I_{AVG(TOT)} = I_{LED}$$

The average output current multiplied by the forward diode voltage determines the loss of the output diode:

Eq. 26: $$P_{LOSS(DIODE)} = I_{AVG(TOT)} \cdot V_F = I_{LED} \cdot V_F$$

For continuous LED currents, the diode junction temperature can then be estimated:

Eq. 27: $$T_{J(DIODE)} = T_{AMB} + \theta_{JA} \cdot P_{LOSS(DIODE)}$$

The external Schottky diode junction temperature should be below 110°C, and may vary depending on application and/or system guidelines. The diode θ_{JA} can be minimized with additional metal PCB area on the cathode.

However, adding additional heat-sinking metal around the anode may degrade EMI performance. The reverse leakage current of the rectifier must be considered to maintain low quiescent (input) current and high efficiency under light load, the rectifier reverse current increases dramatically at elevated temperatures.

Selecting the External N-Channel Boost MOSFET

Selection of the external power MOSFET is controlled by tradeoffs among efficiency, cost and size. The critical parameters for the selection of a MOSFET are: minimum threshold voltage, $V_{GSth(MIN)}$, minimum drain to source breakdown voltage, B_{VDSS}, on-resistance, $R_{DS(ON)}$, and total gate charge, Q_G.

The peak-to-peak gate drive level is set by the V_{CC} voltage, which is typically 5V for the AAT2404 under normal operating conditions. This requires the minimum threshold voltage of the MOSFET to be less than 5V; logic level MOSFETS have minimum threshold voltages less than 5V. However, in switch mode operation the gate-to-drain ("Miller") charge parameter of the MOSFET Q_{GD} will affect the V_{GSTH} parameter. Consult the Gate Charge Characteristics plot found in the datasheet of the MOSFET and ensure that the Q_{GD} plateau is less than 4.5V (the lower the better).

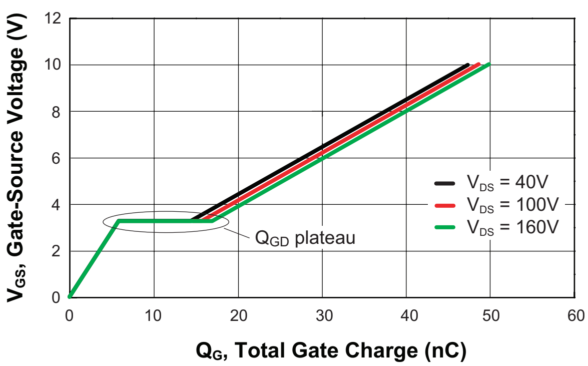


Figure 4: Example Gate Charge Characteristics (I_D = 21A).

Estimating gate drive power required to turn the MOSFET on and the power losses in the MOSFET is a good way of balancing the tradeoffs and comparing the relative merit between MOSFET devices.

The amount of current needed to turn on a MOSFET is:

$$\textbf{Eq. 28: } I_G = Q_G \cdot f_{SW}$$

Where

I_G = Required current to turn on a MOSFET
Q_G = Total Gate charge of the MOSFET
f_{SW} = Switching frequency

Then the gate drive power required to turn on a MOSFET is:

$$\textbf{Eq. 29: } P_G = V_G \cdot Q_G \cdot f_{SW}$$

Where:

P_G = Gate charge loss in the linear regulator of the AAT2404
V_G = Gate drive voltage V_G = V_{CC} = 5V
Q_G = Total gate charge of the MOSFET
f_{SW} = Switching frequency

During the off state of the boost controller the voltage across the MOSFET is equal to the output voltage, V_{LED}, when neglecting the intrinsic diode voltage drop. The BV_{DSS} parameter of the MOSFET must be greater than the voltage output. Using 80% derating on V_{LED} for ringing on the switch node, the minimum BV_{DSS} voltage of the MOSFET is

$$\textbf{Eq. 30: } BV_{DSS} \geq \frac{V_{LED}}{0.8}$$

BV_{DSS} = Minimum drain to source breakdown voltage of the MOSFET
V_{LED} = Voltage output of the boost regulator

First order power losses in a MOSFET can be attributed to conduction loss, switching loss, and the gate drive loss. Although the gate drive loss is not strictly in the MOSFET it is included in the MOSFET power loss calculation.

$$\textbf{Eq. 31: } P_{MOSFET} = P_C + P_{SW} + P_G$$

Where:

P_{MOSFET} = Power dissipated by the MOSFET
P_C = Conduction loss of the MOSFET
P_{SW} = Switching loss of the MOSFET
P_G = Gate charge loss in the linear regulator of the AAT2404

Conduction loss is the I^2R loss when the MOSFET is turned on and is approximated by the following equation:

$$\textbf{Eq. 32: } P_C = D \cdot \left[\left(\frac{I_{LED}}{1 - D}\right)^2 \cdot R_{DS(ON)}\right]$$

Where:

P_C = Conduction loss of the MOSFET
D = Boost switching duty cycle
I_{LED} = Current output of the boost regulator
$R_{DS(ON)}$ = Maximum high temperature on-resistance of the MOSFET

Switching loss occurs during the transition between the MOSFET being turned on and then turned off.

$$\textbf{Eq. 33: } P_{SW} = \frac{1}{2} \cdot V_{IN} \cdot \frac{I_{LED}}{(1 - D)} \cdot (t_R + t_F) \cdot f_{SW}$$

Where:

P_{SW} = Switching loss of the MOSFET
V_{IN} = Minimum input voltage
I_{LED} = Current output of the boost regulator
D = Boost switching duty cycle
t_R = Rise time of the MOSFET (refer to the selected MOSFET's datasheet)
t_F = Fall time of the MOSFET (refer to the selected MOSFET's datasheet)
f_{SW} = Switching frequency

After selecting the MOSFET the package power dissipation in the operating circuit can be estimated.

$$\textbf{Eq. 34: } P_{D(TOTAL)} = P_{OUT}\left(\frac{1}{\eta} - 1\right) = V_{LED} \cdot I_{LED} \cdot \left(\frac{1}{\eta} - 1\right)$$

Where:

$P_{D(TOTAL)}$ = Total power dissipation for the system, (output power plus power loss of the switching MOSFET)
η = Boost efficiency (refer to the efficiency curve for the given output load current in the Typical Characteristics section of this datasheet)
V_{LED} = Voltage output of the boost regulator
I_{LED} = Current output of the boost regulator

The power that will be dissipated by the MOSFET should be determined; the package P_D rating of the MOSFET selected should exceed this value:

$$\textbf{Eq. 35: } P_{MOSFET} < P_{D(TOTAL)} - P_L - P_D - (V_{IN} \cdot I_Q)$$

Where:

P_{MOSFET} = Power dissipated by the MOSFET
$P_{D(TOTAL)}$ = Total system power calculated in Equation 34
P_L = Power dissipation of the inductor based on the DC resistance (DCR)
P_D = Power dissipation of the reverse blocking Schottky diode
V_{IN} = Input supply voltage
I_Q = Device quiescent supply current

Selecting the Output Capacitor

The output capacitor in a current regulator is selected to control the output ripple current (Δi_F) when the inductor is charging as opposed to a voltage regulator where ΔV_O is controlled. As a result, the output capacitor is subjected to much larger ripple currents.

Assuming a constant discharging current when the MOSFET switch is on, the voltage ripple across the capacitor is:

$$\textbf{Eq. 36: } \Delta V_{PK\text{-}PK} = \frac{I_{LED} \cdot D_{MAX}}{C_{OUT} \cdot f_{SW}}$$

Solving for C_{OUT}:

$$\textbf{Eq. 37: } C_{OUT} = \frac{I_{LED} \cdot D_{MAX}}{\Delta V_{PK\text{-}PK} \cdot f_{SW}}$$

Where

$\Delta V_{PK\text{-}PK}$ = V_{LED} voltage ripple
I_{LED} = Output supply current
D_{MAX} = Maximum boost switching duty cycle
f_{SW} = Switching frequency

The output capacitor must be capable of handling the maximum output RMS current. Use Equation 38 to estimate the $I_{CLED(RMS)}$ value.

$$\textbf{Eq. 38: } I_{CLED(RMS)} = \sqrt{(1 - D) \cdot \left(I_{LED}^2 \cdot \frac{D}{(1 - D)^2} + \frac{\Delta i_L^2}{3}\right)}$$

Where

I_{LED} = Current output of the boost regulator
Δi_L = Nominal ripple current in the inductor
D = Boost switching duty cycle

The equivalent series resistance (ESR) and the equivalent series inductance (ESL) of the output capacitor directly control the output ripple. Use capacitors with low ESR and ESL specification at the output for high efficiency and low ripple voltage. Surface mount tantalum polymer electrolytic, and polymer tantalum Sanyo-OSCON capacitors are recommended at the output.

Selecting the Input Capacitor

The input capacitors in a boost regulator control the input voltage ripple (ΔV_{IN}) and prevent impedance mismatch (also called power supply interaction) between the AAT2404 and the stray inductance of the input wire connections. Selection of input capacitors is based on their capacitance, ESR, and RMS current rating. The minimum input capacitance is based on ΔV_{IN} or prevention of power supply interaction. In general, the requirement for the greatest capacitance comes from the power supply interaction.

The stray inductance, L_S, and resistance, R_S, of the input source must be estimated, and if this information is not available, good design practice may assume the inductance and resistances to be 1μH and 0.1Ω, respectively.

Minimum input capacitance is then estimated as:

Eq. 39: $$C_{IN(MIN)} = \frac{2 \cdot L_S \cdot V_{LED} \cdot I_{LED}}{V_{IN}^2 \cdot R_S}$$

Where:

L_S = Power supply parasitic inductance (assumed to be 1μH)
V_{LED} = Voltage output of the boost regulator
I_{LED} = Current output of the boost regulator
V_{IN} = Input supply voltage
R_S = Power supply stray resistance (assumed to be 0.1Ω)

Selecting the Compensation Resistor and Capacitor

Regulator stability is achieved with a simple RC compensation network from the COMP pin to ground. Once the boost regulator design requirements have been established and the inductor and output capacitor values have been chosen, the LC filter must be compensated for to stabilize the boost regulator. The AAT2404 senses the inductor current and eliminates the double pole LC filter and simplifies the compensation to a single pole RC caused by the output capacitance and the output load resistance. However, since the AAT2404 is designed to work in the continuous conduction mode (CCM) an undesirable right-half plane zero is produced in the regulation feedback loop. This requires compensating the AAT2404 such that the crossover frequency occurs well below the frequency of the right-half plane zero.

Eq. 40: $$F_{zRHP} = \left(\frac{V_{IN}}{V_{LED}}\right)^2 \cdot \frac{R_L}{2\pi \cdot L}$$

Where:

V_{IN} = Input supply voltage
V_{LED} = Voltage output of the boost regulator
R_L = Output load resistance
L = Inductance

To stabilize the regulator, ensure that the regulator crossover frequency is less than or equal to one-tenth of the right-half plane zero or less than or equal to one-tenth of the switching frequency whichever is lower.

The regulator loop gain is determined by Equation 41:

Eq. 41:
$$|A_{VL}| = \frac{V_{REF}}{V_{LED}} \cdot \frac{V_{IN}}{V_{LED}} \cdot G_{MEA} \cdot R_C \cdot G_{CS} \cdot \frac{1}{2\pi \cdot f_C \cdot C_{OUT}} = 1$$

Where

V_{REF} = Feedback voltage reference set by R_{SET}
V_{IN} = Input supply voltage
V_{LED} = Voltage output of the boost regulator
R_C = Compensation resistor
G_{MEA} = Error amplifier transconductance: 176μA/V
G_{CS} = Current sense amplifier transconductance: 3.0A/V
f_C = Selected crossover frequency
C_{OUT} = Output capacitor

The AAT2404 regulator loop solving for compensation resistor, R_C:

Eq. 42: $$R_C = \frac{2\pi \cdot f_C \cdot C_{OUT} \cdot V_{LED} \cdot V_{LED}}{V_{REF} \cdot V_{IN} \cdot G_{MEA} \cdot G_{CS}}$$

Once the compensation resistor is known, set the zero formed by the compensation capacitor and resistor to one-tenth of the crossover frequency, or:

Eq. 43: $$C_C = \frac{10}{2\pi \cdot f_C \cdot R_C}$$

If the zero of the ESR of the output capacitor is near f_C, then it needs to be cancelled out by putting and an extra cap in parallel with R_C and C_C. To determine the zero of the ESR of the output capacitor:

Eq. 44: $$f_{ESR} = \frac{1}{2\pi \cdot R_{ESR} \cdot C_{OUT}}$$

To cancel the ESR zero:

Eq. 45: $$C_2 = \frac{R_{ESR} \cdot C_{OUT}}{R_C}$$

Where:

R_{ESR} = ESR of the output capacitor
C_{OUT} = Output capacitor
R_C = Compensation resistor

Layout Fundamentals

1. Minimize the length of both traces in series with the output capacitor terminals to avoid high dV/dt (fast changing voltages) and reduce capacitive coupling and electric fields. One trace is from the cathode of the rectifying diode to the positive terminal of the capacitor, the other trace is from PGND to the negative terminal.
2. Minimize the loop area of high di/dt (fast charging currents) to reduce inductance and magnetic field. Use wide traces for high current traces.
3. Maintain a ground plane and connect to the IC PGND pin(s) as well as the PGND connections of C_{IN} and C_{OUT}.
4. Consider additional PCB exposed area for the AAT2404 to maximize heat sinking capability. Connect the exposed paddle (bottom of the die) to PGND or GND. Connect AGND as close as possible to the package and maximize the overall heat sinking space.
5. To maximize package thermal dissipation and power handling capacity of the AAT2404's TQFN34-24 and external MOSFET and diode packages (Q1 and D1), solder the exposed paddle of the IC onto the thermal landing of the PCB, where the thermal landing is connected to the ground plane. If heat is still an issue, multi-layer boards with dedicated ground planes are recommended. Also, adding more thermal vias on the thermal landing helps transfer heat to the PCB effectively. The MOSFET and diode can also be mounted upright and connected to heat sinks.

Typical System Configurations for Direct and Edge Backlighting Applications

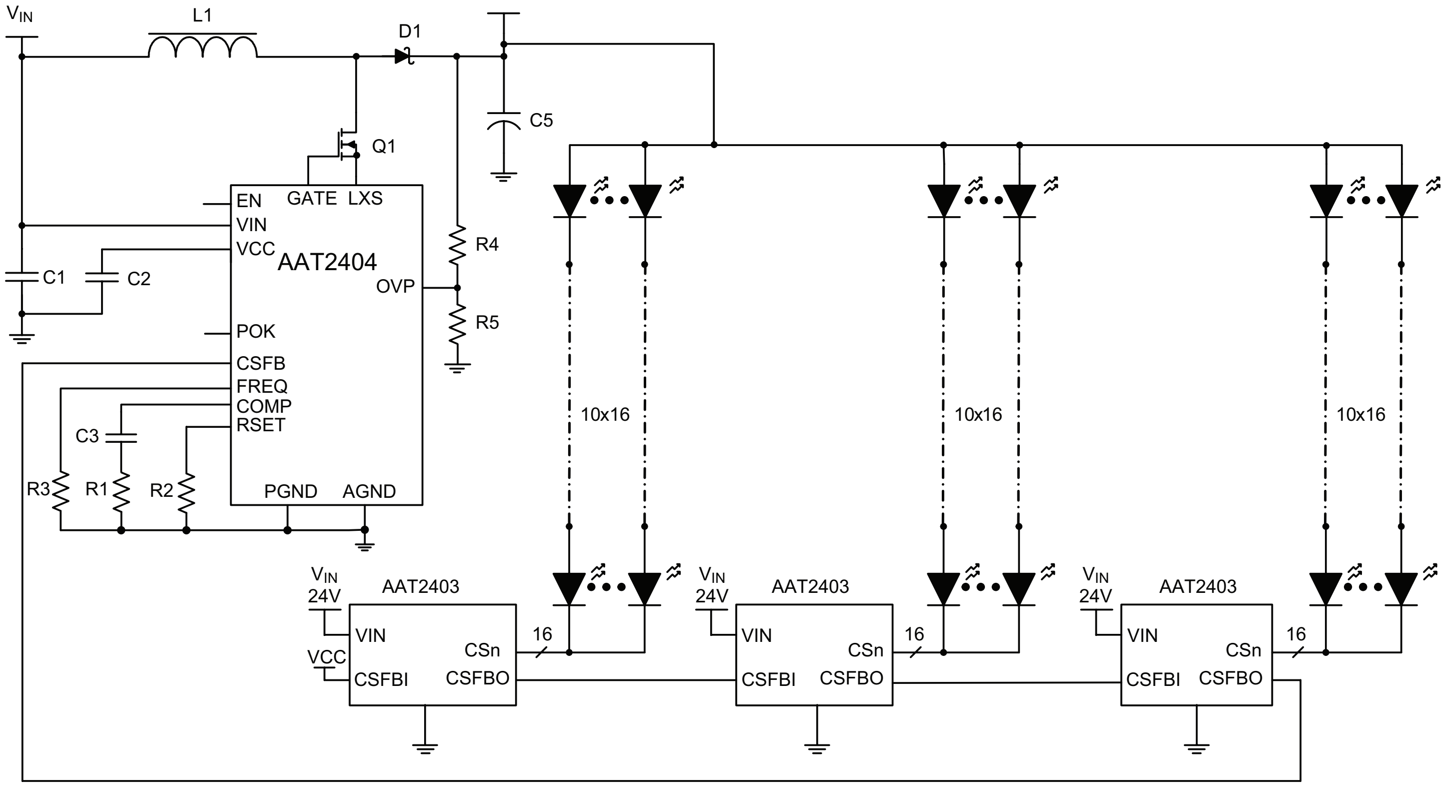


Figure 5: Direct LCD TV LED Backlight System Using the AAT2404 to Drive Three 10Sx16P LED Arrays with Three AAT2403 Current Sink Controllers.

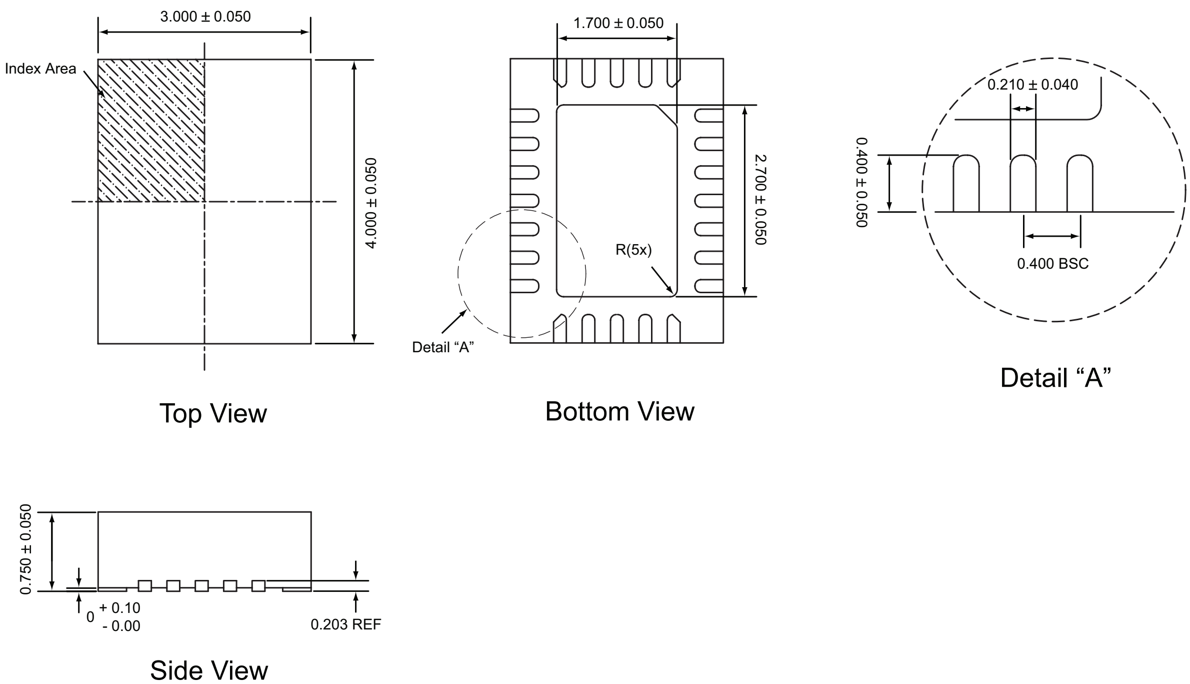
Ordering Information

Package	Marking[1]	Part Number (Tape and Reel)[2]
TQFN34-24	9UXYY	**AAT2404IMK-T1**

Skyworks Green™ products are compliant with all applicable legislation and are halogen-free. For additional information, refer to *Skyworks Definition of Green™*, document number SQ04-0074.

Package Information

TQFN34-24[3]



ALL DIMENSIONS IN MILLIMETERS.

1. XYY = assembly and date code.
2. Sample stock is generally held on part numbers listed in **BOLD**.
3. The leadless package family, which includes QFN, TQFN, DFN, TDFN, and STDFN, has exposed copper (unplated) at the end of the lead terminals due to the manufacturing process. A solder fillet at the exposed copper edge cannot be guaranteed and is not required to ensure a proper bottom solder connection.