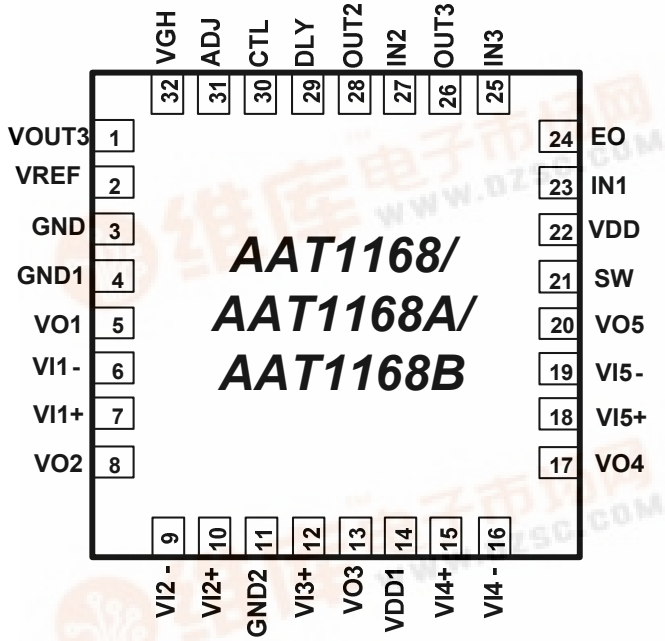
TRIPLE-CHANNEL TFT LCD POWER SOLUTION WITH OPERATIONAL AMPLIFIERS

FEATURES

- Built in 3A, 0.2Ω Switching NMOS
- Positive LDO Driver Up to 28V/5mA
- Negative LDO Driver Down to –14V/5mA
- 1 V_{COM} and 4 V_{GAMMA} Operational Amplifiers
- 28V High Voltage Switch for VGH
- Internal Soft-Start Function
- 1.2MHz Fixed Switching Frequency
- 3 Channels Fault and Thermal Protection
- Low Dissipation Current
- QFN-32 Package Available

PIN CONFIGURATION



GENERAL DESCRIPTION

The AAT1168/AAT1168A/AAT1168B is a triple-channel TFT LCD power solution that provides a step-up PWM controller, two LDO drivers (one for positive high voltage and one for negative voltage), five operational amplifiers, and one high voltage switch up to 28V for TFT LCD display.

The PWM controller consists of an on-chip voltage reference, oscillator, error amplifier, current sense circuit, comparator, under-voltage lockout protection and internal soft-start circuit. The thermal and power fault protection prevents internal circuit being damaged by excessive power.

The LDO drivers generate two regulated output voltage set by external resistor dividers. VGH voltage does not activate until DLY voltage exceeds 1.25V.

The AAT1168/AAT1168A/AAT1168B contains 4+1 operational amplifiers. VO1, VO2, VO4, and VO5 are for gamma corrections and VO3 is for V_{COM}. In the short circuit condition, operational amplifiers are capable of sourcing ±100mA current for V_{GAMMA}, and ±200mA current for V_{COM}.

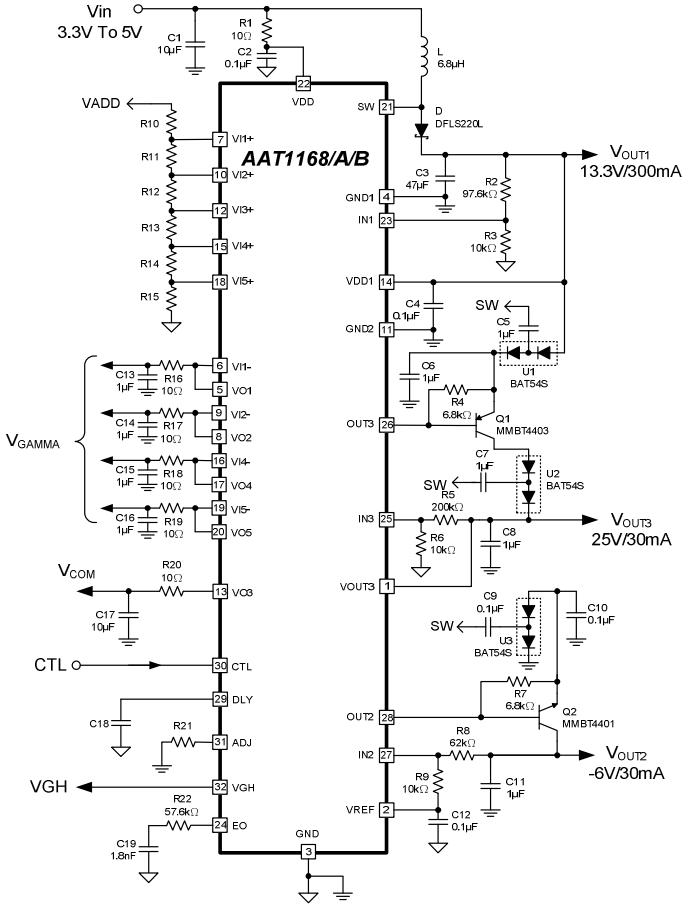
With the minimal external components, the AAT1168/A/B offers a simple and economical solution for TFT LCD power.

ORDERING INFORMATION

DEVICE TYPE	PART NUMBER	PACKAGE	PACKING	TEMP. RANGE	MARKING	MARKING DESCRIPTION
AAT1168	AAT1168 -Q5-T	Q5:VQFN32-5*5	T: Tape and Reel	−40°C to +85°C	AAT1168 XXXXX XXXX	Device Type Lot no.(6~9digits) Date Code (4digits)
AAT1168A	AAT1168A -Q5-T	Q5:VQFN32-5*5	T: Tape and Reel	−40°C to +85°C	AAT1168A XXXXX XXXX	Device Type Lot no.(6~9digits) Date Code (4Digits)
AAT1168B	AAT1168B -Q5-T	Q5:VQFN32-5*5	T: Tape and Reel	−40°C to +85°C	AAT1168B XXXXX XXXX	Device Type Lot no.(6~9digits) Date Code (4Digits)

NOTE: The product is lead free and halogen free.

TYPICAL APPLICATION



ABSOLUTE MAXIMUM RATINGS

PARAMETER	SYMBOL	VALUE	UNIT
VDD to GND	V_{DD}	7	V
VDD1, SW to GND (for AAT1168/AAT1168B)	V_{H1}	14.5	V
VDD1, SW to GND (for AAT1168A)	V_{H1}	25	V
VOUT3, OUT3, VGH to GND (for AAT1168/AAT1168B)	V_{H2}	28	V
VOUT3, OUT3, VGH to GND (for AAT1168A)	V_{H2}	40	V
OUT2 to GND	V_{H3}	–14	V
Input Voltage 1 (IN1, IN2, IN3, DLY, CTL)	V_{I1}	V_{DD} +0.3	V
Input Voltage 2 (VI1+, VI1 – , VI2+, VI2 – , VI3+, VI3 – , VI4+, VI4 – , VI5+, VI5 –)	V_{I2}	V_{H1} +0.3	V
Output Voltage 1 (EO, V_{REF})	V_{O1}	V_{DD} +0.3	V
Output Voltage 2 (ADJ, VO1, VO2, VO3, VO4, VO5)	V_{O2}	V_{H1} +0.3	V
Operating Free-Air Temperature Range	T_C	–40°C to +85°C	°C
Storage Temperature Range	$T_{STORAGE}$	–45°C to +125°C	°C
Maximum Junction Temperature	T_J	+125	°C
Package Thermal Resistance	J_A	34	°C/W
Package Thermal Resistance	J_C	1.1	°C/W
Power Dissipation	P_d	1,618	mW

NOTE: Stresses above those listed under ABSOLUTE MAXIMUM RATINGS may cause permanent damage to the devices. Exposure to ABSOLUTE MAXIMUM RATINGS conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS

(V_{DD} = 2.6V to 5.5V, T_C = –40°C to 85°C , unless otherwise specified. Typical values are tested at 25°C ambient temperature, V_{DD} = 5V, V_{DD1} = 10V.)

PARAMETER	SYMBOL	TEST CONDITION	MIN	TYP	MAX	UNIT
VDD Input Voltage Range	V_{DD}		2.6		5.5	V
VDD1 Input Voltage Range	V_{DD1}	AAT1168/AAT1168B	8		14	V
		AAT1168A	8		23	V
VDD Under Voltage Lockout	V_{UVLO}	Falling	2.1	2.2	2.3	V
		Rising	2.3	2.4	2.5	V
VDD Operating Current	I_{VDD}	V_{IN1} = 1.5V, Not Switching		0.56	0.80	mA
		V_{IN1} = 1.0V, Switching		5.60	10.0	mA
VDD1 Operating Current	I_{VDD1}	V_{VI1+} ~ V_{VI5+} = 4V		7	10	mA
Thermal Shutdown	T_{SHDN}			160		°C

Reference Voltage

PARAMETER	SYMBOL	TEST CONDITION	MIN	TYP	MAX	UNIT
Reference Voltage	V_{REF}	$I_{V_{REF}}$ = 100µA	1.231	1.250	1.269	V
Line Regulation	V_{RI}	$I_{V_{REF}}$ = 100µA, V_{DD} = 2.6V~5.5V	-	2	5	mV
Load Regulation	V_{RO}	$I_{V_{REF}}$ = 0~100µA	-	1	5	mV

Oscillator

PARAMETER	SYMBOL	TEST CONDITION	MIN	TYP	MAX	UNIT
Oscillation Frequency	f_{OSC}		1.05	1.20	1.35	MHz
Maximum Duty Cycle	D_{MAX}		84	87	90	%

ELECTRICAL CHARACTERISTICS

(V_{DD} = 2.6V to 5.5V, T_C = –40°C to 85°C , unless otherwise specified. Typical values are tested at 25°C ambient temperature, V_{DD} = 5V, V_{DD1} = 10V.)

Soft Start & Fault Detect

PARAMETER	SYMBOL	TEST CONDITION	MIN	TYP	MAX	UNIT
Channel 1 Soft Start Time	t_{SS1}			14		ms
Channel 2 Soft Start Time	t_{SS2}			14		ms
Channel 3 Soft Start Time	t_{SS3}			14		ms
Channel 1 to Channel 2 Delay	t_{D12}	AAT1168A Only		7		ms
Channel 2 to Channel 3 Delay	t_{D23}	AAT1168A Only		7		ms
During Fault Protect Trigger Time	t_{FP}	AAT1168/AAT1168B		55		ms
		AAT1168A		165		ms
IN1 Fault Protection Voltage	V_{F1}	AAT1168/AAT1168B	1.00	1.05	1.10	V
		AAT1168A	1.13	1.17	1.20	V
IN2 Fault Protection Voltage	V_{F2}		0.40	0.45	0.50	V
IN3 Fault Protection Voltage	V_{F3}		1.00	1.05	1.10	V

Error Amplifier (Channel 1)

PARAMETER	SYMBOL	TEST CONDITION	MIN	TYP	MAX	UNIT
Feedback Voltage	V_{IN1}		1.221	1.233	1.245	V
Input Bias Current	I_{B1}	V_{IN1} = 1V to 1.5V	–40	0	40	nA
Feedback-Voltage Line Regulation	V_{RI1}	Level to Produce V_{EO} = 1.233V 2.6V < V_{DD} < 5.5V		0.05	0.15	%/V
Transconductance	G_m	ΔI = 5μA		105		μS
Voltage Gain	A_V			1,500		V/V

ELECTRICAL CHARACTERISTICS

(V_{DD} = 2.6V to 5.5V, T_C = –40°C to 85°C , unless otherwise specified. Typical values are tested at 25°C ambient temperature, V_{DD} = 5V, V_{DD1} = 10V.)

N-MOS Switch (Channel 1)

PARAMETER	SYMBOL	TEST CONDITION	MIN	TYP	MAX	UNIT
Current Limit	I_{LIM}			3.0		A
On-Resistance	R_{ON}	I_{SW} = 1.0A		0.2		Ω
Leakage Current	I_{SWOFF}	V_{SW} = 12V		0.01	20.00	µA

Negative Charge Pump (Channel 2)

PARAMETER	SYMBOL	TEST CONDITIONS	MIN	TYP	MAX	UNIT
IN2 Threshold Voltage	V_{IN2}	I_{OUT2} = –100µA	235	250	265	mV
IN2 Input Bias Current	I_{B2}	V_{IN2} = –0.25V to 0.25V	–40	0	40	nA
OUT2 Leakage Current	I_{OFF2}	V_{IN2} = 0V, OUT2 = –12V		–20	–50	µA
OUT2 Source Current	I_{OUT2}	V_{IN2} = 0.35V, OUT2 = –10V	1	4		mA

Positive Charge Pump (Channel 3)

PARAMETER	SYMBOL	TEST CONDITIONS	MIN	TYP	MAX	UNIT
IN3 Threshold Voltage	V_{IN3}	I_{OUT3} = 100µA	1.22	1.25	1.28	V
IN3 Input Bias Current	I_{B3}	V_{IN3} = 1V to1.5V	–40	0	40	nA
OUT3 Leakage Current	I_{OFF3}	V_{IN3} = 1.4V, OUT3 = 28V		40	80	µA
OUT3 Sink Current	I_{OUT3}	V_{IN3} = 1.1V, OUT3 = 25V	1	4		mA

ELECTRICAL CHARACTERISTICS

(V_{DD} = 2.6V to 5.5V, T_C = –40°C to 85°C , unless otherwise specified. Typical values are tested at 25°C ambient temperature, V_{DD} = 5V, V_{DD1} = 10V.)

High Voltage Switch Controller

PARAMETER	SYMBOL	TEST CONDITIONS	MIN	TYP	MAX	UNIT
DLY Source Current	I_{DLY}		–4	–5	–6	µA
DLY Threshold Voltage	V_{DLY}		1.22	1.25	1.28	V
DLY Discharge R_{ON}	R_{DLY}			8		Ω
CTL Input Low Voltage	V_{IL}				0.5	V
CTL Input High Voltage	V_{IH}		2			V
CTL Input Bias Current	I_{B4}	V_{CTL} = 0 to V_{DD}	–40	0	40	nA
Propagation Delay CTL to VGH	t_{PP}	OUT3 = 25V		100		ns
VOUT3 to VGH Switch R-on	R_{ONSC}	V_{DLY} = 1.5V, V_{CTL} = VDD		15	30	Ω
ADJ to VGH Switch R-on	R_{ONDC}	V_{DLY} = 1.5V, V_{CTL} = GND		30	60	Ω

ELECTRICAL CHARACTERISTICS

(V_{DD} = 2.6V to 5.5V, T_C = –40°C to 85°C , unless otherwise specified. Typical values are tested at 25°C ambient temperature, V_{DD} = 5V, V_{DD1} = 10V.)

V_{COM} and V_{GAMMA} Buffer

PARAMETER	SYMBOL	TEST CONDITIONS	MIN	TYP	MAX	UNIT
Input Offset Voltage	V_{OS}	V_{VI1+} ~ V_{VI5+} = 4V	-	2	12	mV
Input Bias Current	I_{B5}	V_{VI1+} ~ V_{VI5+} = 4V	–40	0	40	nA
Output Swing (for AAT1168)	V_{OL}	I_{VO1}, I_{VO2}, I_{VO4}, I_{VO5} = 10mA, V_{VI1}, V_{VI2}, V_{VI4}, V_{VI5} = 4V	-	4.02	4.05	V
		I_{VO3} = 50mA, V_{VI3} = 4V	-	4.03	4.06	
	V_{OH}	I_{VO1}, I_{VO2}, I_{VO4}, I_{VO5} = –10mA V_{VI1}, V_{VI2}, V_{VI4}, V_{VI5} = 4V	3.95	3.98	-	
		I_{VO3} = –50mA , V_{VI3} = 4V	3.94	3.97	-	
Short Circuit Current	I_{SHORT}	I_{VO1}, I_{VO2}, I_{VO4}, I_{VO5}	-	±100	-	mA
		I_{VO3}	-	±200	-	mA
Slew Rate	SR	V_{VI1+} , V_{VI3+} = 2V to 8V, V_{VI3+} ~ V_{VI5+} = 8V to 2V, 20% to 80%	-	12	-	V/µs
Settling Time	t_S	V_{VI1+} ~ V_{VI5+} = 3.5V to 4.5V, 90%	-	5	-	µs

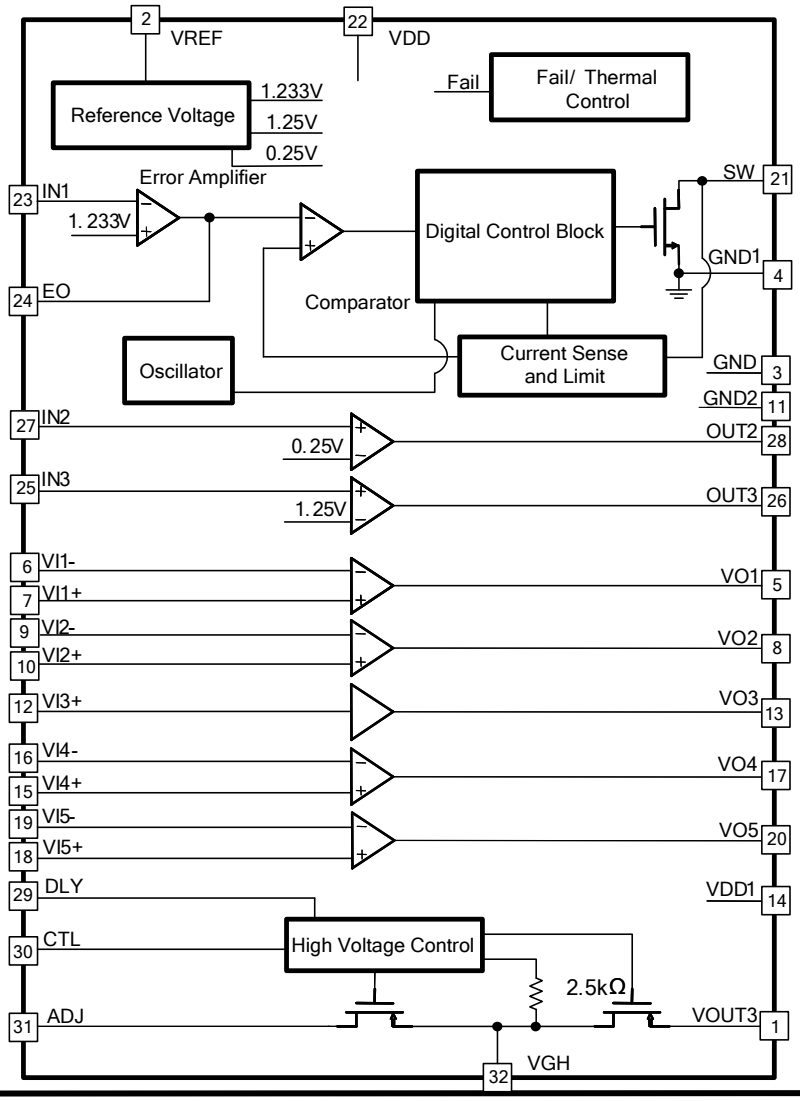
PIN DESCRIPTION

PIN NO. QFN-32	NAME	I/O	DESCRIPTION
1	VOUT3	-	Channel 3 Output Voltage (gate high voltage input)
2	VREF	O	Internal Reference Voltage Output
3	GND	-	Ground
4	GND1	-	SW MOS Ground
5	VO1	O	Operational Amplifier 1 Output
6	VI1–	I	Operational Amplifier 1 Negative Input
7	VI1+	I	Operational Amplifier 1 Positive Input
8	VO2	O	Operational Amplifier 2 Output
9	VI2–	I	Operational Amplifier 2 Negative Input
10	VI2+	I	Operational Amplifier 2 Positive Input
11	GND2	-	Ground for Operational Amplifiers
12	VI3+	I	V_{COM} Operational Amplifier Positive Input
13	VO3	I	V_{COM} Operational Amplifier Output
14	VDD1	-	High Voltage Power Supply Input
15	VI4+	I	Operational Amplifier 4 Positive Input
16	VI4–	I	Operational Amplifier 4 Negative Input
17	VO4	O	Operational Amplifier 4 Output
18	VI5+	I	Operational Amplifier 5 Positive Input
19	VI5–	I	Operational Amplifier 5 Negative Input
20	VO5	O	Operational Amplifier 5 Output
21	SW	-	Main PWM Switching Pin
22	VDD	-	Power Supply Input
23	IN1	I	Main PWM Feedback Pin
24	EO	O	Main PWM Error Amplifier Output
25	IN3	I	Positive Charge Pump Feedback Pin
26	OUT3	O	Positive Charge Pump Output
27	IN2	I	Negative Charge Pump Feedback Pin

PIN NO. QFN-32	NAME	I/O	DESCRIPTION
28	OUT2	O	Negative Charge Pump Output
29	DLY	I	High Voltage Switch Delay Control
30	CTL	I	High Voltage Switch Control Pin
31	ADJ	O	Gate High Voltage Fall Time Setting Pin
32	VGH	O	Switching Gate High Voltage for TFT

FUNCTION BLOCK DIAGRAM

AAT1168



TYPICAL APPLICATION CIRCUIT

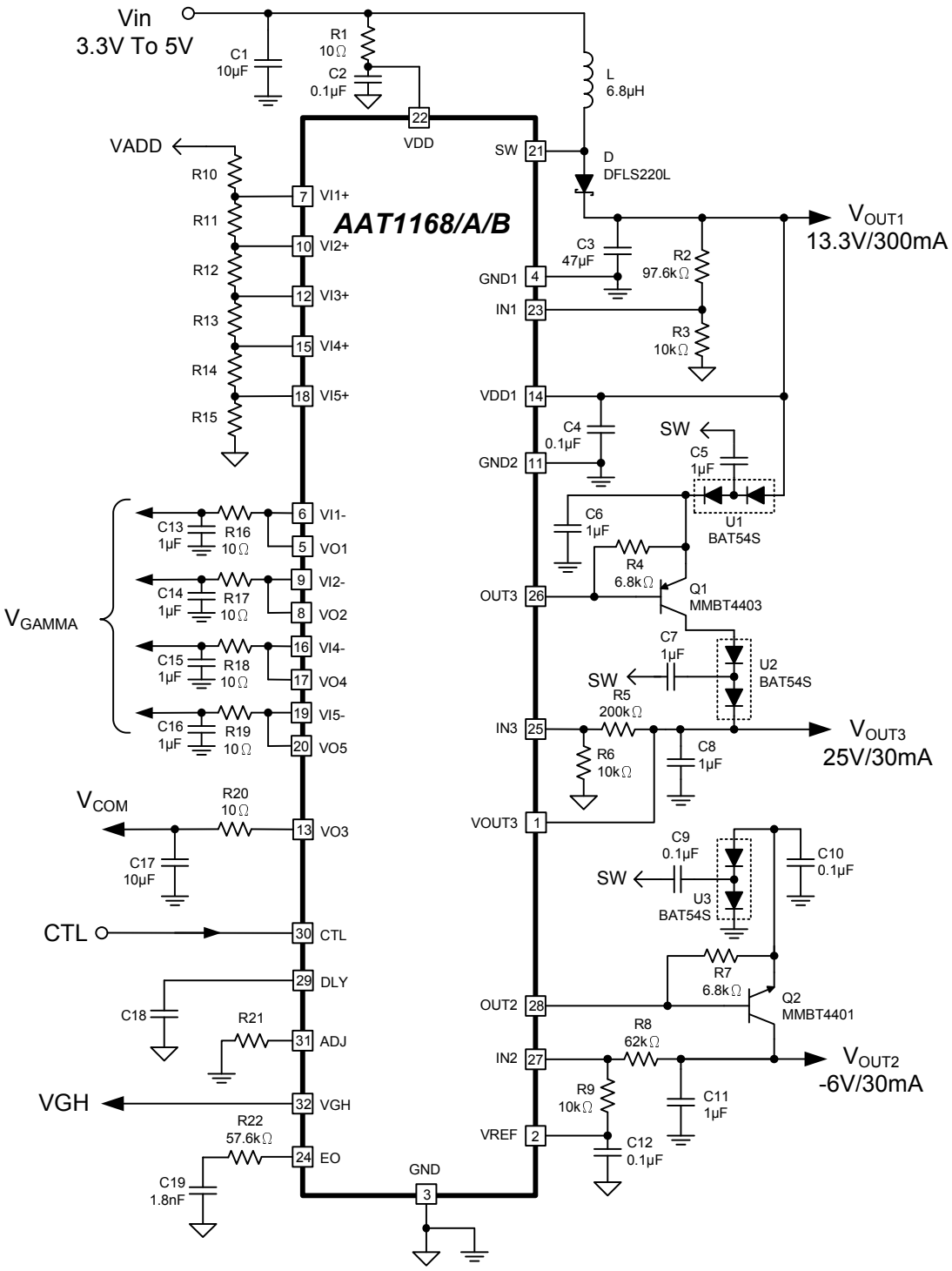
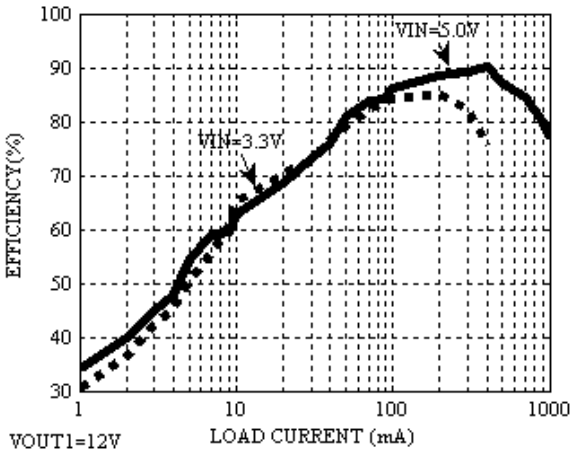


Figure 1. Typical Application Circuit

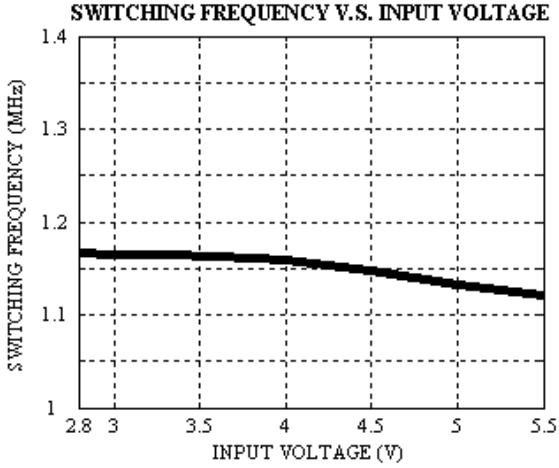
TYPICAL OPERATING CHARACTERISTICS

(V_{IN} = 5V, V_{OUT1} = 12V, V_{OUT2} = −7V, V_{OUT3} = 27V, T_C = +25°C , unless otherwise noted.)

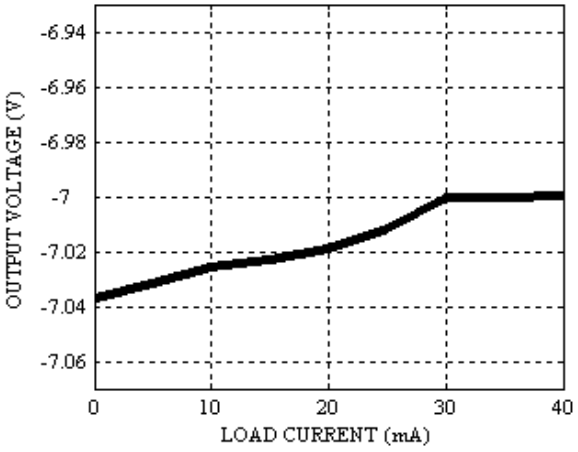
STEP UP EFFICIENCY V.S. LOAD CURRENT



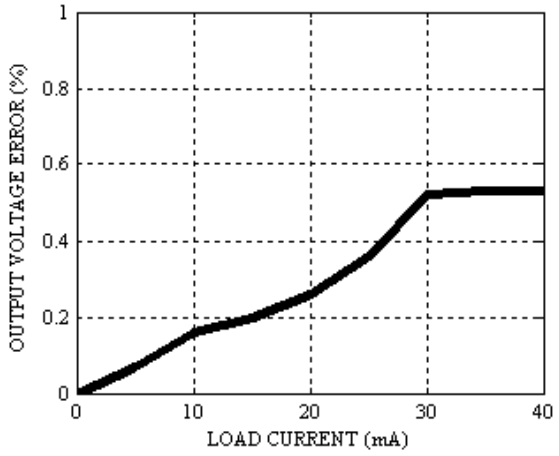
SWITCHING FREQUENCY V.S. INPUT VOLTAGE



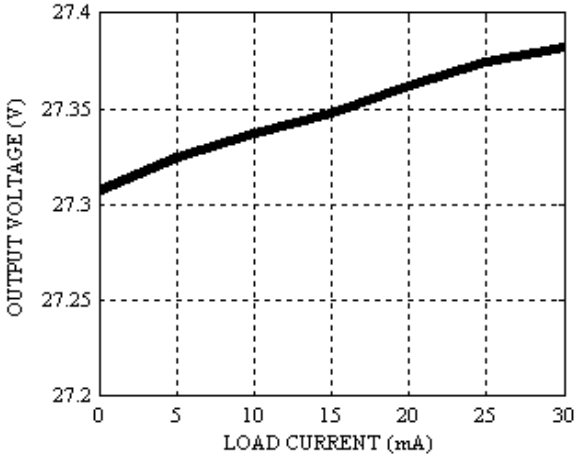
OUTPUT VOLTAGE 2 REGULATOR



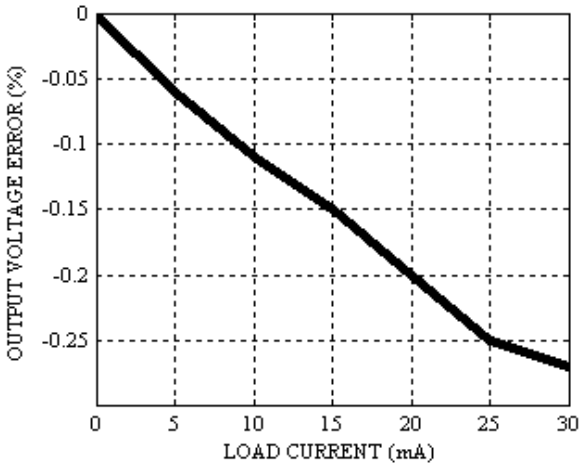
OUTPUT VOLTAGE 2 REGULATOR



OUTPUT VOLTAGE 3 REGULATOR



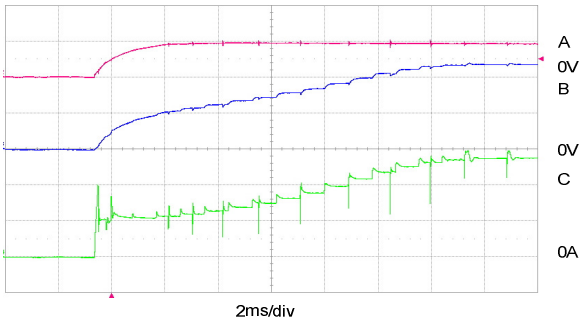
OUTPUT VOLTAGE 3 REGULATOR



TYPICAL OPERATING CHARACTERISTICS

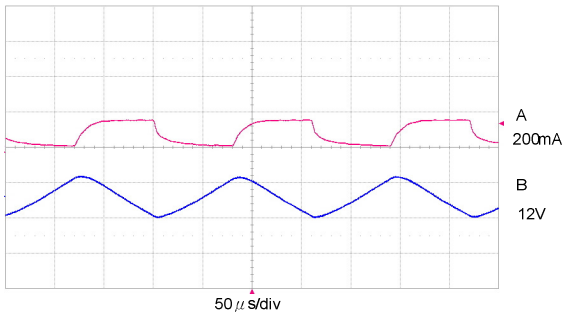
(V_{IN} = 5V, V_{OUT1} = 12V, V_{OUT2} = −7V, V_{OUT3} = 27V, T_C = +25°C , unless otherwise noted.)

STEP UP REGULATOR SOFT-START (HEAVY LOAD)



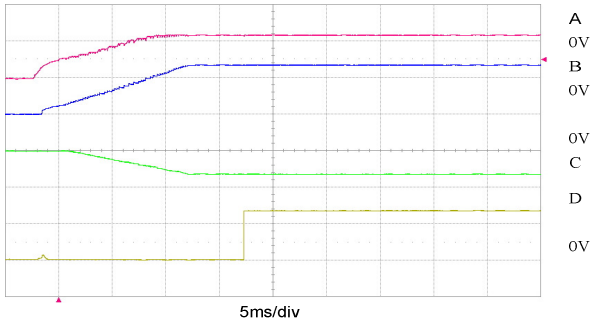
A:V_{IN},5V/div
B:V_{OUT1},5V/div
C:INDUCTOR CURRENT,1A/div

STEP UP REGULATOR PULSED LOAD TRANSIENT RESPONSE



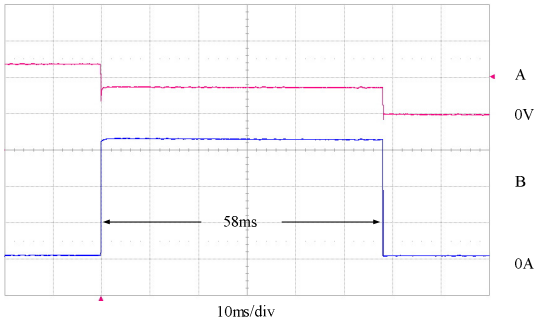
A:LOAD CURRENT,100mA/div
B:V_{OUT1},200mV/div,AC-COUPLED

POWER ON SEQUENCE



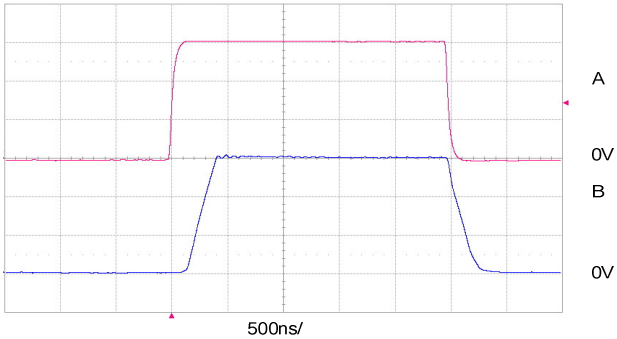
A:V_{OUT1},10V/div
B:V_{OUT3},20V/div
C:V_{OUT2},10V/div
D:V_{O3},20V/div

TIME DELAY LATCH RESPONSE TO OVERLOAD



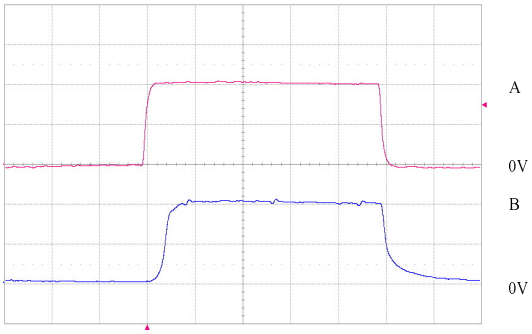
A:V_{OUT1},5V/div
B:INDUCTOR CURRENT,1A/div

OPERATIONAL-AMPLIFIER LARGE SIGNAL STEP RESPONSE



A:INPUT SIGNAL,2V/div
B:OUTPUT SINAL,2V/div
V_{SUP}=6V

OPERATIONAL-AMPLIFIER SMALL SIGNAL STEP RESPONSE



A:INPUT SIGNAL,200mV/div
B:OUTPUT SINAL,200mV/div

DESIGN PROCEDURE

Boost Converter Design

Setting the Output Voltage and Selecting the Lead Compensation Capacitor

The output voltage of boost converter is set by the resistor divider from the output (V_{OUT1}) to GND with the center tap connected to the IN1. Where V_{IN1}, the boost converter feedback regulation voltage is 1.233V. Choose R_2 (Figure 2) between 5.1kΩ to 51kΩ and calculate R_1 to satisfy the following equation.

$$R_1 = R_2\left(\frac{V_{OUT1}}{V_{IN1}} - 1\right)$$

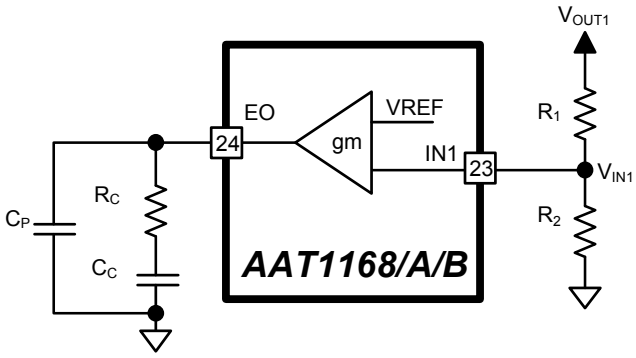


Figure 2. Feedback Circuit

Inductor Selection

The minimum inductance value is selected to make sure that the system operates in continuous conduction mode (CCM) for high efficiency and to prevent EMI. The equation of inductor used a parameter κ, which is the ratio of the inductor peak to peak ripple current to the input DC current. The best trade-off between voltage ripple of transient output current and permanent output current has a κ between 0.4 and 0.5.

$$L \geq \frac{\eta V_O}{\kappa I_O f_S} D(1-D)^2,$$

$$D = 1 - \frac{V_{IN}}{V_O},$$

$$\kappa = \frac{I_{Lpeak}}{I_{IN}}$$

η : Boost converter efficiency

κ : The ratio of the inductor peak to peak ripple current to the input DC current

V_{IN} : Input voltage

V_O : Output voltage

I_O : Output load current

f_S : Switching frequency

D : Duty cycle

I_{LPEAK} : Inductor peak to peak ripple current

I_{IN} : Input DC current

The AAT1168 SW current limit (I_{LIM}) and inductor' saturation current rating (I_{LSAT}) should exceed $I_{L(peak)}$, and the inductor's DC current rating should exceed I_{IN}. For the best efficiency, choose an inductor with less DC series resistance (r_L).

I_{LIM} and $I_{LSAT} > I_{L(peak)}$

$I_{LDC} > I_{IN}$

$$I_{L(peak)} = I_{IN} + \frac{V_{IN} D}{2 L f_s},$$

$$I_{IN} = \frac{I_O}{\eta(1-D)},$$

$$P_{DCR} \approx \left(\frac{I_O}{\eta(1-D)}\right)^2 r_L$$

I_{LDC} : DC current rating of inductor

P_{DCR} : Power loss of inductor series resistance

Table 1.Inductor Data List

C6-K1.8L	r_L	DC CURRENT RATING
3.9μH	41 mΩ	2.5A
6.8μH	68 mΩ	2.2A
10μH	81 mΩ	1.8A
MITSUMI Product-Max Height: 1.9mm		

Example 1: In the typical application circuit (Figure 1) the output load current is 300mA with 13.3V output

voltage and input voltage of 5V. Choose a κ of 0.465 and efficiency of 90%.

$$L \geq \frac{0.9 * 13.3}{0.465 * 0.3 * 1.1^6} 0.624(0.376)^2 \approx 6.8\,\mu H$$

$$I_{IN} = \frac{I_O}{\eta(1-D)} = 0.89A$$

$$I_{L(peak)} = I_{IN} + \frac{V_{IN}D}{2Lf_s} = 1.095A$$

$P_{DCR} = 0.043W$ or 1% power loss

Schottky Diode Selection

Schottky has to be able to dissipate power. The dissipated power is the forward voltage and input DC current. To achieve the best efficiency, choose a Schottky diode with less recovery capacitor (CT) for fast recovery time and low forward voltage (VF).

For boost converter, the reverse voltage rating (V_R) should be higher than the maximum output voltage, and current rating should exceed the input DC current.

$$P_{DIODE} = P_{DSW} + P_{DCOM}$$

$$P_{DSW} = (1-D)V_F Q_R f_s$$

$$Q_R = V_R C_T$$

$$P_{DCOM} = V_F I_O /(1-D)$$

P_{DIODE} : Total power loss of diode for boost converter
P_{DSW} : Switching loss of diode for boost converter
P_{DCOM} : Conduction loss of diode for boost converter

Table 2. Schottky Data List

SMA	V_F	V_R	C_T
B220A	0.24V	14V	150pF
B240A	0.24V	28V	150pF
DIODES Product, Max-Height: 2.3mm			

For example,

$P_{DIODE} = P_{DSW} + P_{DCOM} = 0.203W$ or 5.1% power loss.

Input Capacitor Selection

The input capacitors have two important functions in PWM controller. First, an input capacitor provides the power for soft start procedure and supply the current for the gate-driving circuit. A 10µF ceramic capacitor is used in typical circuit. Second, an input bypass capacitor reduces the current peaks, the input voltage drop, and noise injection into the IC. A low ESR ceramics capacitor 0.1µF is used in typical circuit. To ensure the low noise supply at V_{DD}, V_{DD} is decoupled from input capacitor using an RC low pass filter.

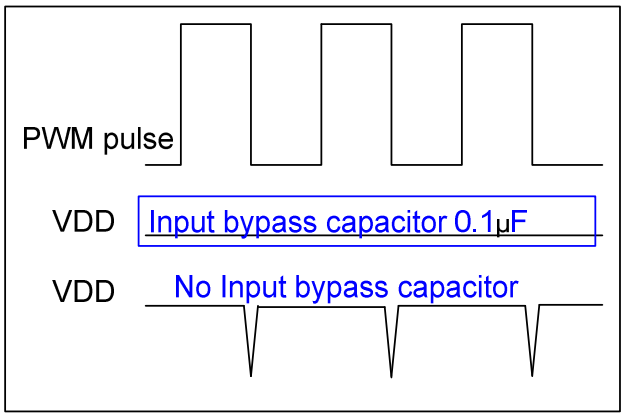


Figure 3. Input Bypass Capacitor Affects the V_{DD} Drop

Output Capacitor

The output capacitor maintains the DC output voltage. A Low ESR (r_C) ceramic capacitor can reduce the output ripple and power loss. There are two parameters which can affect the output voltage ripple: 1. the voltage drops when the inductor current flows through the ESR of output capacitor; 2. charging and discharging of the output capacitor also affect the output voltage ripple.

$$V_{RIPPLE} = V_{RIPPLE}(C_{OUT}) + V_{RIPPLE}(ESR)$$

$$V_{RIPPLE}(C_{OUT}) \approx \frac{I_O D}{f_S C_{OUT}}$$

$$V_{RIPPLE}(ESR) \approx I_{L(peak)} r_C$$

$$P_{ESR} = \left(I_{Lpeak}\right)^2 \cdot r_C$$

ESR: Equivalent Series Resistance

Example 2: C_{OUT} = 38µF, r_C = 20mΩ
$V_{RIPPLE}(C_{OUT})$ = 4mV
$V_{RIPPLE}(ESR)$ = 22mV
V_{RIPPLE} = 26mV
P_{ESR} = 0.023W or 0.6% power loss

Boost Converter Power loss

The largest portions of power loss in the boost converter are the internal power MOSFET, the inductor, the Schottky diode, and the output capacitor. If the boost converter has 90% efficiency, there is approximately 3.3% power loss in the internal MOSFET, 1% power loss in the inductor, 5.1% power loss in the Schottky diode, and 0.6% power loss in the output capacitor.

Loop Compensation Design

The voltage-loop gain with current loop closed sets the stability of steady state response and dynamic performance of transient response. The loop compensation design is as follows:

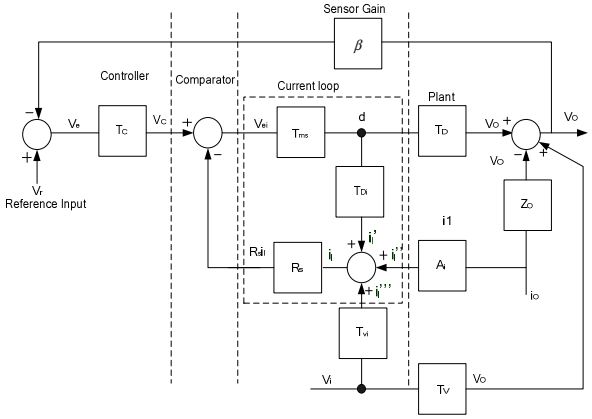


Figure 4. Closed-current Loop for Boost with PCM

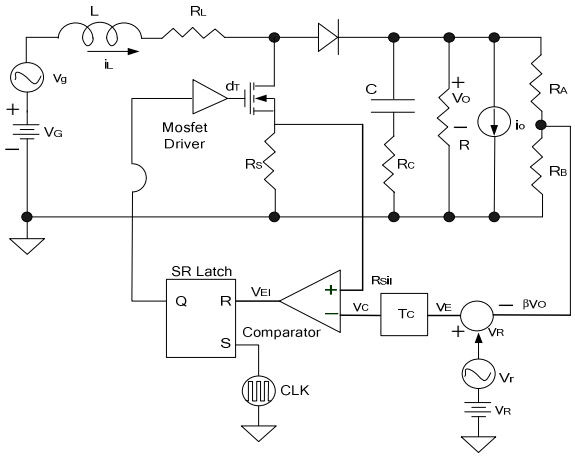


Figure 5. Block Diagram of Boost Converter with Peak Current Mode (PCM)

Power Stage Transfer Functions

The duty to output voltage transfer function T_p is:

$$T_p(s) = \frac{V_O}{d} = T_{p0}\frac{(s+w_{esr})(s-w_{z2})}{s^2+2\xi w_n s+{w_n}^2}$$

$$\text{Where } T_{p0} = V_O\frac{-r_C}{(1-D)(R_L+r_C)},\ w_{esr} = \frac{1}{Cr_C}$$

And

$$w_{z2} = \frac{R_L(1-D)^2 - r}{L},\ w_n = \sqrt{\frac{(1-D)^2R_L + r}{LC(R_L+r_C)}}$$

$$\xi = \frac{C[r(R_L+r_C)+R_Lr_c(1-D)^2]+L}{2\sqrt{LC(R_L+r_C)[r+(1-D)^2R_L]}},$$

$$r = r_L + Dr_{DS} + (1-D)R_F$$

r_L is the inductor equivalent series resistance, r_C is capacitor ESR, R_L is the converter load resistance, C is output filter capacitor, r_{DS} is the transistor turn on resistance, and R_F is the diode forward resistance.
The duty to inductor current transfer function T_{pi} is:

$$T_{pi}(s) = \frac{i_l}{d} = T_{pi0}\frac{s+w_{zi}}{s^2+2\xi w_n s+{w_n}^2}$$

$$\text{Where } T_{pi0} = \frac{V_O(R_L+2r_C)}{L(R_L+r_C)},\ w_{zi} = \frac{1}{C(R_L/2+r_C)}$$

Current Sampling Transfer Function

Error voltage to duty transfer function F_m is:

$$F_m(s) = \frac{d}{v_{ei}} = \frac{2f_s^2\left(s^2 + 2\xi w_n s + w_n^2\right)}{T_{pi0}R_{CS}s(s+w_{zi})(s+w_{sh})}$$

Where $w_{sh} = \frac{3w_s}{\pi}\left(\frac{1-\alpha}{1+\alpha}\right), \alpha = \frac{M_2 - M_a}{M_1 + M_a}$

$w_s = 2\pi f_s$

Therefore, F_m depends on duty to inductor current transfer function T_{pi}, and f_s is the clock switching frequency; R_{CS} is the current-sense amplifier transresistance.

For the boost converter, $M_1 = V_{IN}/L$ and $M_2 = (V_O - V_{IN})/L$.

For AAT1168, $R_{CS} = 0.24$ V/A, M_a is slope compensation, $M_a = 0.8\times10^{6}$.

The closed-current loop transfer function T_{icl} is:

$$T_{icl}(s) = \frac{12f_s^2}{R_{CS}T_{pi0}} x \frac{\left(s^2 + 2\xi w_n s + w_n^2\right)}{(s+w_{zi})\left(s^2 + w_{sh}s + 12f_s^2\right)}$$

The Voltage-Loop Gain with Current Loop Closed

The control to output voltage transfer function T_d is:

$$T_d(s) = \frac{V_O(s)}{V_C(s)} = T_{icl}(s)T_p(s)$$

The voltage-loop gain with current loop closed is:

$$L_{vi}(s) = \beta T_C(s)T_d(s)$$

$$= \beta g_m R_C \frac{s+w_c}{s}\frac{12f_s^2 T_{p0}}{R_{CS}T_{pi0}} \times \frac{(s+w_{z1})(s-w_{z2})}{(s+w_{zi})(s^2 + sw_{sh} + 12f_s^2)}$$

Where $\beta = \frac{V_{FB}}{V_O}$

The compensator transfer function

$$T_C(s) = \frac{V_C}{v_{fb}} = g_m R_C \frac{s+w_c}{s}$$

Where

$$w_c = \frac{1}{R_C C_C}$$

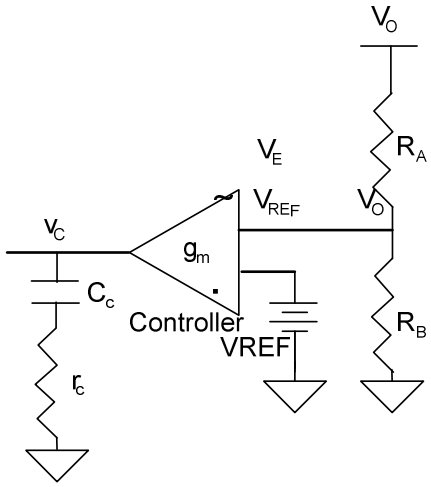


Figure 6. Voltage Loop Compensator

Compensator design guide:

1. Crossover frequency $f_{ci} < \frac{1}{2}f_s$

2. Gain margin>10dB

3. Phase margin>45°

4. The $|L_{vi}(s)| = 1$ at crossover frequency, Therefore, the compensator resistance, R_C is determined by:

$$R_C = \frac{V_O}{V_{FB}}\frac{2\pi f_{ci}CR_{CS}}{g_m k}\frac{(R_L + 2r_C)}{\left[(1-D)R_L - \frac{r}{(1-D)}\right]}$$

Table 3 K factor Table

C	Best Corner Frequency	K factor
21.533µF	23.740 kHz	4.692
25.079µF	21.842 kHz	5.083
32.587µF	20.095 kHz	6.042
36.312µF	15.649 kHz	5.230
38.469µF	13.247 kHz	4.703

5. The output filter capacitor is chosen so C R_L pole cancels R_C C_C zero

$$\varepsilon R_C C_C = C\left(\frac{R_L}{2} + r_C\right), \text{ and}$$

$$C_C = \frac{C}{\varepsilon R_C}\left(\frac{R_L}{2} + r_C\right)$$

$$\varepsilon = (1 \sim 3)$$

Example 3:

V_{IN} = 5V, V_O = 13.3V, I_O = 300mA, f_s = 1,190kHz,
V_{FB} = 1.233V, L = 6.65µH, G_m = 85µS,
r_L = 76.689 mΩ
r_C = 9.13mΩ, R_F = 0.7667Ω, C_C = 1.95nF,
R_C = 7.6kΩ, C = 38.5µF, ε = 3, R_{CS} = 0.23V/A.

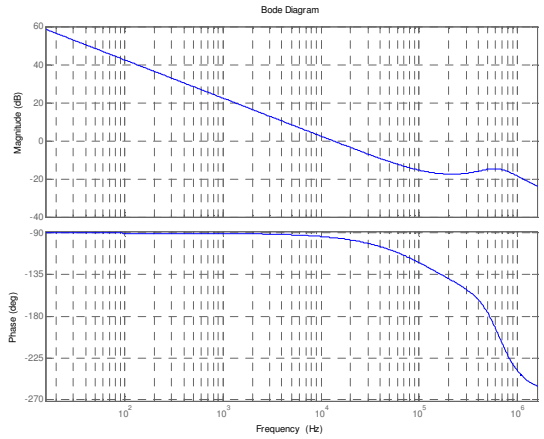


Figure 7. Bode Plot of Loop Gain Using Matlab® Simulation

Positive and Negative LDO driver Output Voltage Selection

The output voltage of positive LDO driver is set by a resistive divider from the output (Vout3) to GND with the center tap connected to the IN3, where V_{IN3}, the positive LDO driver feedback regulation voltage, is 1.25V. Choose R_6 (Figure 8) between 10kΩ and 51kΩ. And calculate R_5 with the following equation.

$$R_5 = R_6\left(\frac{Vout3}{V_{IN3}} - 1\right)$$

The output voltage of negative LDO driver is set by a resistive divider from the output (VGL) to VREF with the center tap connected to the IN2, where V_{IN2}, the negative LDO driver feedback regulation voltage, is 0.25V. Choose R_9 (Figure 9) between 10kΩ and 51kΩ and calculate R_8 with the following equation.

$$R_8 = R_9\left(\frac{V_{IN2} - V_{GL}}{V_{REF} - V_{IN2}}\right)$$

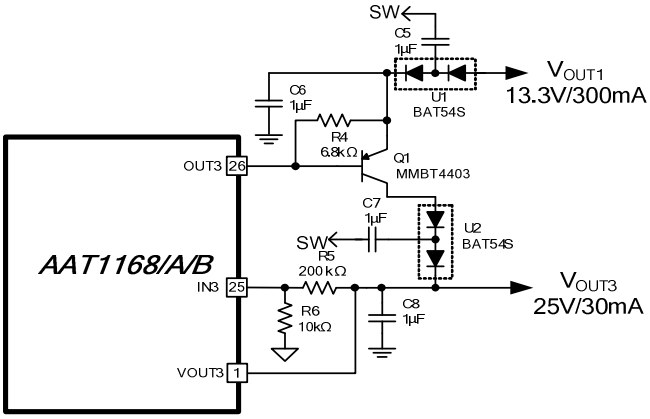


Figure 8. The Positive LDO Driver

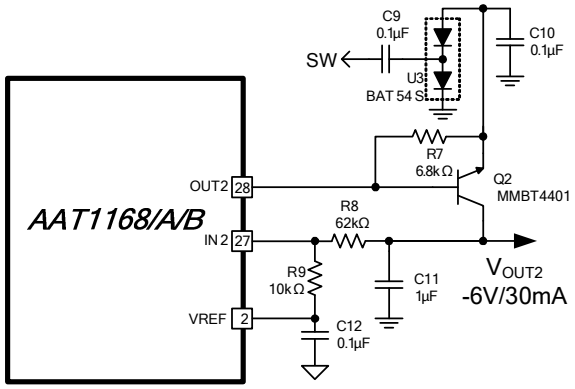


Figure 9. The Negative LDO Driver

Example 4:
For system design

$V_{OUT3} = 25V$, $R_5 = 200k\Omega$, $R_6 = 10k\Omega$,
$V_{OUT2} = -6V$, $R_8 = 62k\Omega$, $R_9 = 10k\Omega$

Flying Capacitors

Increasing the flying capacitor (C_5 , C_7 , C_9) values can lower output voltage ripples. The 1µF ceramic capacitors works well in positive LDO driver. A 0.1µF ceramic capacitor works well in negative LDO driver.

LDO Driver Diode

To achieve high efficiency, a Schottky diode should be used. BAT54S (Figure 8 and 9) has fast recovery time and low forward voltage for best efficiency.

LDO Driver Base-Emitter Resistors

For AAT1168, the minimum drive current for positive and negative LDO driver are 1mA, thus the minimum base-emitter resistance can be calculated by the following equation:

$$R_{4(min)} \geq V_{BE(max)} / ((I_{OUT3(min)} - I_C) / hfe_{(min)})$$
$$R_{7(min)} \geq V_{BE(max)} / ((I_{OUT2(min)} - I_C) / hfe_{(min)})$$

Table 4 Pass Transistor Specifications

	MMBT4401	MMBT4403
$V_{BE(max)}$	0.65V	0.5V
$hfe_{(min)}$	130	90
DIODES Product, Case: SOT23		

Example 5:
Output current of V_{OUT3} and V_{OUT2} are 30mA, the minimum base-emitter resistor can be calculated as

$$R_{4(min)} \geq 0.5 / ((|1mA - 30mA|) / 90) \geq 750\,\Omega$$
$$R_{7(min)} \geq 0.65 / ((|1mA - 30mA|) / 130) \geq 845\,\Omega$$

The minimum value can be used, however, the larger value has the advantage of reducing quiescent current. So we choose $6.8k\Omega$ to be R_4.

Charge Pump Output Capacitor

Using low ESR ceramic capacitor to reduce the output voltage ripple is recommended. With ceramic capacitor, output voltage ripple is dominated by the capacitance value. The minimum capacitance value can be calculated by the following equation:

$$Cout \geq \frac{I_{load}}{2V_{ripple}f_s}$$

Example 6:
The output voltage ripple of V_{OUT3} and VGL is under 1%, the minimum capacitance value can be calculated as

$$Cout(V_{OUT3}) \geq \frac{30mA}{\eta 2 \times 250mV \times 1.19MHz} \approx 0.1\mu F$$
$$Cout(V_{GL}) \geq \frac{30mA}{\eta 2 \times 60mV \times 1.19MHz} \approx 0.33\mu F$$

η : Efficiency, about 60% at charge pump circuit

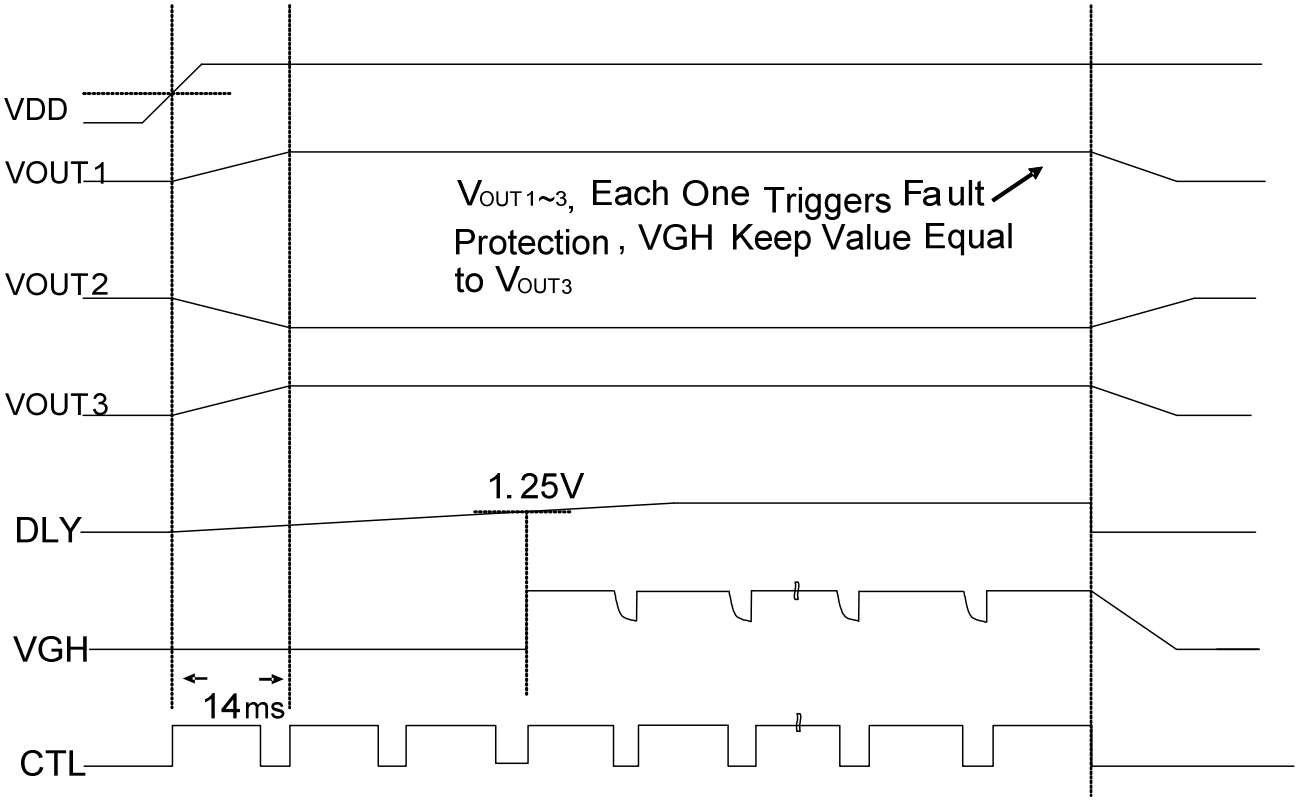
Operational Amplifier

The AAT1168 have five amplifiers independent. The operational amplifiers are usually used to drive V_{COM} and the gamma correction divider string for TFT-LCD. The output resistors and capacitors of amplifiers are as low pass filter and compensator for unity GAIN stable.

Table 5. Recommended Components

DESIGNATION	DESCRIPTION
L	6.8 µH, 1.8A, MITSUMI C6-K1.8L 6R8
U1, U2, U3	200mA 30V Schottky barrier diode (SOT-23), DIODES BAT54S
D	2A 20V rectifier diode DIODES DFLS220L
C3	10 µF, 25V X5R ceramic capacitor
C5, C6, C7	1 µF, 25V X5R ceramic capacitor
C2, C4, C9, C10, C12	0.1 µF, 50V X5R ceramic capacitor

Soft Start Waveform



LAYOUT CONSIDERATION

Layout Guide

The system's performances including switching noise, transient response, and PWM feedback loop stability are greatly affected by the PC board layout and grounding. There are some general guidelines for layout:

Inductor

Always try to use a low EMI inductor with a ferrite core.

Filter Capacitors

Place low ESR ceramics filter capacitors (between 0.1µF and 0.22µF) close to VDD and VREF pins. This will eliminate as much trace inductance effects as possible and give the internal IC rail a cleaner voltage supply. The ground connection of the VDD and VREF bypass capacitor should be connected to the analog ground pin (GND) with a wide trace.

Output Capacitors

Place output capacitors as close as possible to the IC. Minimize the length and maximize the width of traces to get the best transient response and reduce the ripple noise. We choose 10µF ceramics capacitor to reduce the ripple voltage, and use 0.1µF ceramics capacitor to reduce the ripple noise.

Feedback

If external compensation components are needed for stability, they should also be placed close to the IC. Take care to avoid the feedback voltage-divider resistors' trace near the SW. Minimize feedback track lengths to avoid the digital signal noise of TFT control board.

Ground Plane

The grounds of the IC, input capacitors, and output capacitors should be connected close to a ground plane. It would be a good design rule to have a ground plane on the PCB. This will reduce noise and ground loop errors as well as absorb more of the EMI radiated by the inductor. For boards with more than two layers, a ground plane can be used to separate the power plane and the signal plane for improved performance.

PC Board Layout

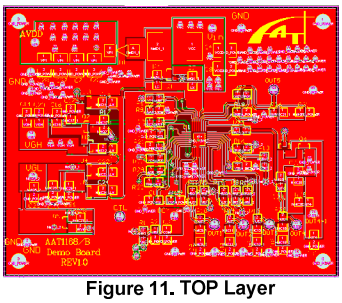


Figure 11. TOP Layer

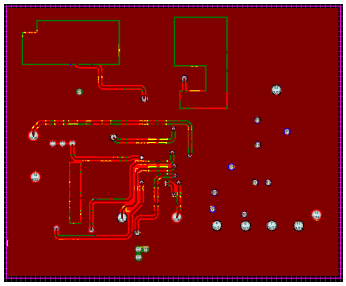


Figure 12. Midlayer1 (Ground Plane)

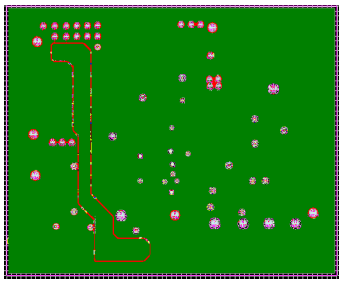


Figure 13. Midlayer2 (Power Plane)

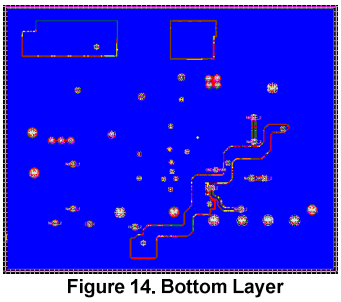
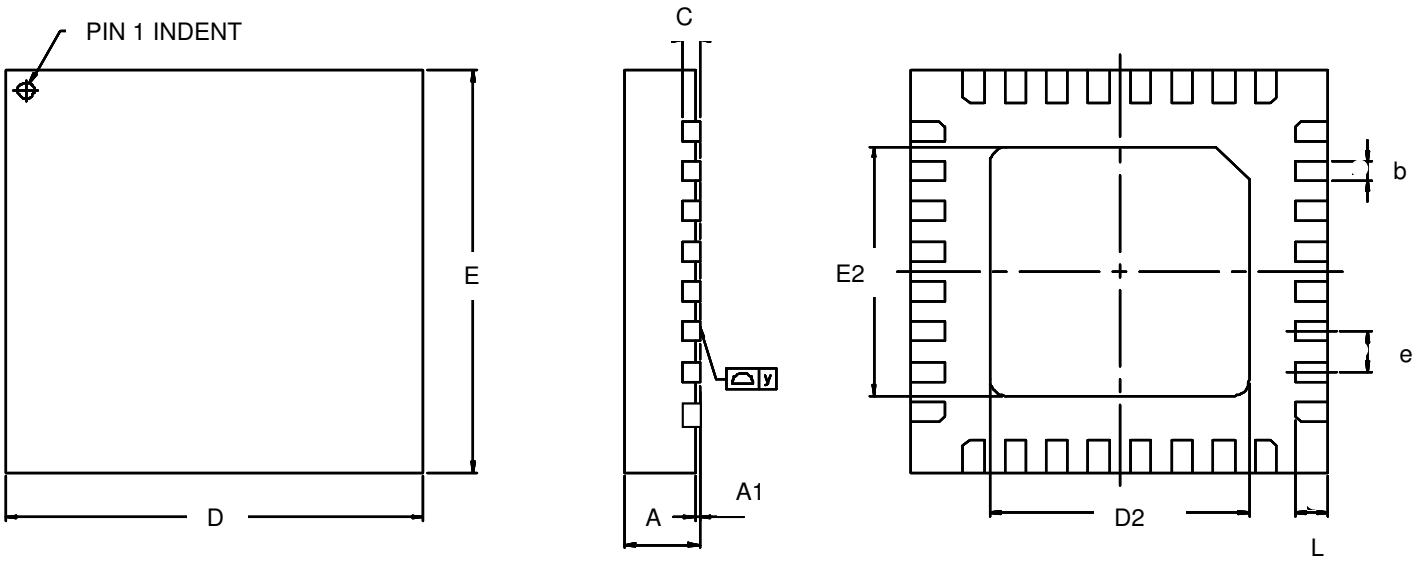


Figure 14. Bottom Layer

PACKAGE DIMENSION

VQFN32



SYMBOL	DIMENSIONS IN MILLIMETERS		
	MIN	TYP	MAX
A	0.8	0.9	1.0
A1	0.00	0.02	0.05
b	0.18	0.25	0.30
C	------	0.2	------
D	4.9	5.0	5.1
D2	3.05	3.10	3.15
E	4.9	5.0	5.1
E2	3.05	3.10	3.15
e	------	0.5	------
L	0.35	0.40	0.45
y	0.000	------	0.075