

TI Designs: TIDA-01426

利用低压直流电源生成线路交流电压且可用于传感器励磁的参考设计



说明

此参考设计展示了如何让设计人员使用分立式组件获得可用于检测火焰的高压信号。低 BOM 成本和小型解决方案尺寸是此参考设计的重要目标。通过采用推挽转换器拓扑，可以实现宽输入范围和短启动时间。

资源

TIDA-01426	设计文件夹
TL494	产品文件夹
TL431	产品文件夹
CSD19538Q3A	产品文件夹
TLV171	产品文件夹



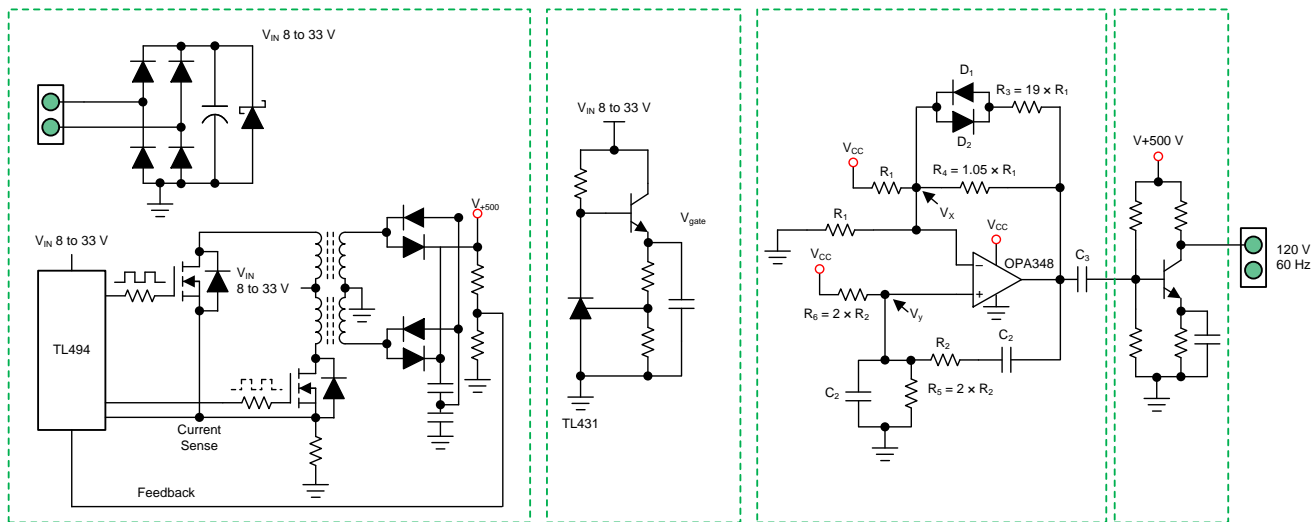
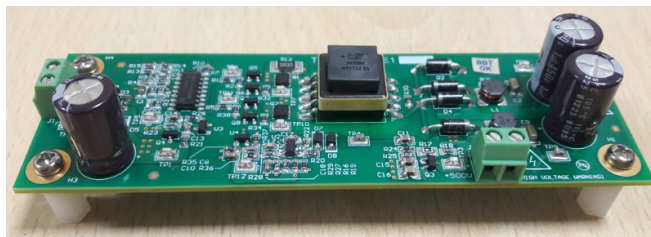
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特性

- 通用输入范围为 10V 到 36V
- 120V、60Hz 输出，THD 最高 4%
- 10V 时的启动时间为 56ms
- 5% 输出精度
- 高达 1W 的输出功率
- 小尺寸和低 BOM 成本

应用

- HVAC 阀门和致动器控制
- HVAC 传感器发送器
- HVAC 系统控制器



Low-Cost, High-Efficiency Push-Pull Boost Converter

Low-Cost Regulated LDO

Low THD, Sine Wave Oscillator
*Can be generated using MCU based SPWM

Class A Amplifier
*Can be Half Bridge for SPWM signals

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1 System Description

A burner system is an integral part of a heating, ventilation, and air conditioning (HVAC) system. A burner system helps generate hot water or steam for heating purposes. The hot water is circulated either for utility purposes or for temperature control. The burner system has control electronics as shown in 图 1 to operate in optimum conditions and prevent any failure with a predictive diagnosis alarm. The electronics unit has actuator control and field sensing cards for the motor drive, damper control, flow control, temperature and pressure sensing, and so on. The unit also ignites and senses flame inside the burner as shown by ECU4 (see 图 1). This reference design focuses on the excitation power supply for the flame rod.

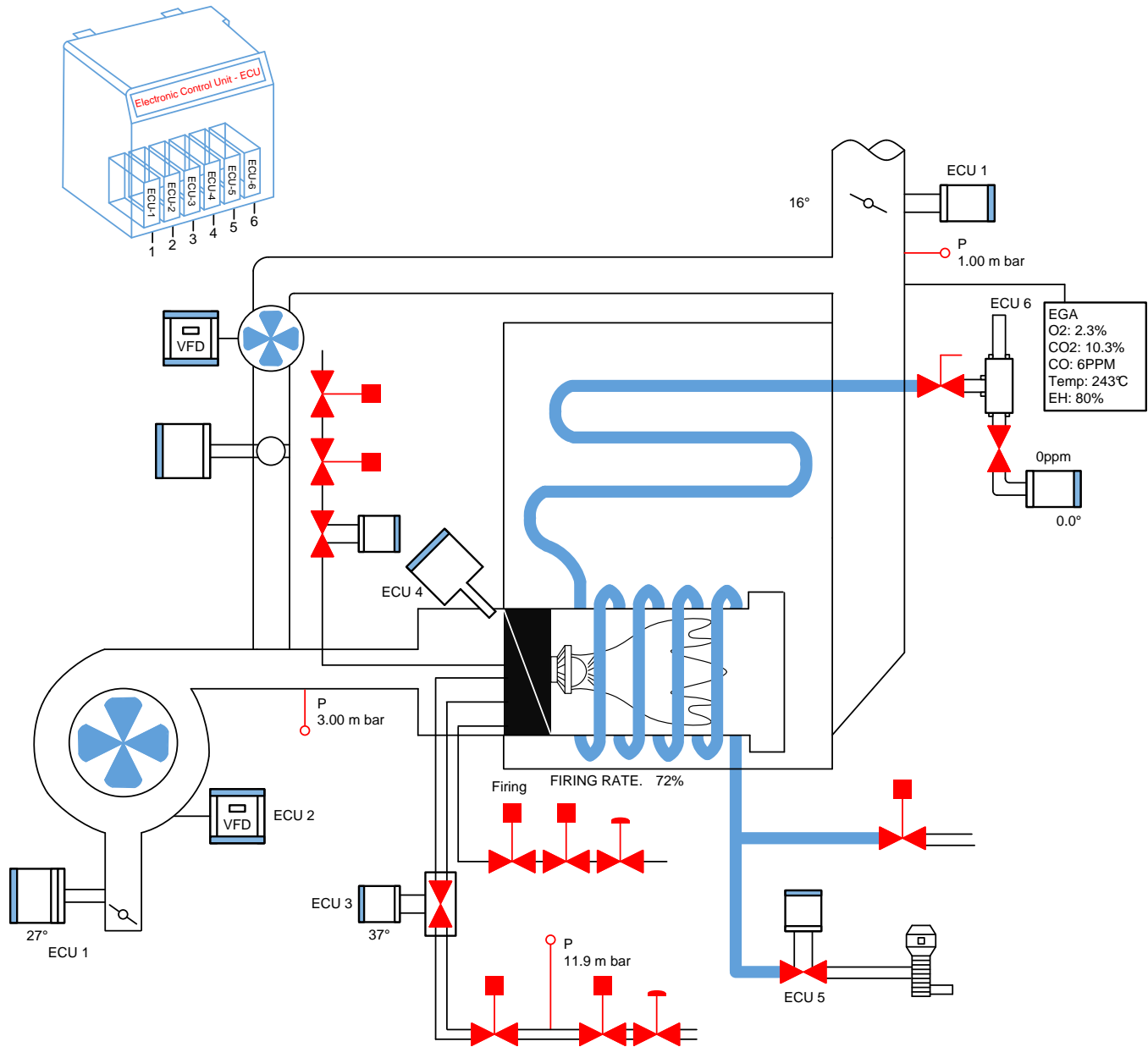


图 1. Burner Control

The flame rod sensor is a high impedance sensor. Under the presence of flame, an ionization effect takes place due to which current flows from the flame rod to earth. This current is proportional to flame intensity. As shown in 图 2, a high-voltage excitation is required for ionization effect. To prevent carbonization effect, AC excitation is applied. This excitation is usually a line supply 50- or 60-Hz signal. A low-frequency AC signal is used to prevent losses due to cable capacitance and skin effect. The geometric ratio of flame rod and earth plate decides the conduction in positive and negative polarity. Usually the ratio is lower to make the flame rod conduct more in positive half cycles and negligible in negative half cycles. This ratio results in output similar to a half wave rectifier. Thus, the flame rod is equivalent to a forward bias diode with a high series impedance, which is the function of flame intensity as shown in 图 2. A signal chain amplifies the lower AC current and controls the fuel supply for the burner firing rate.

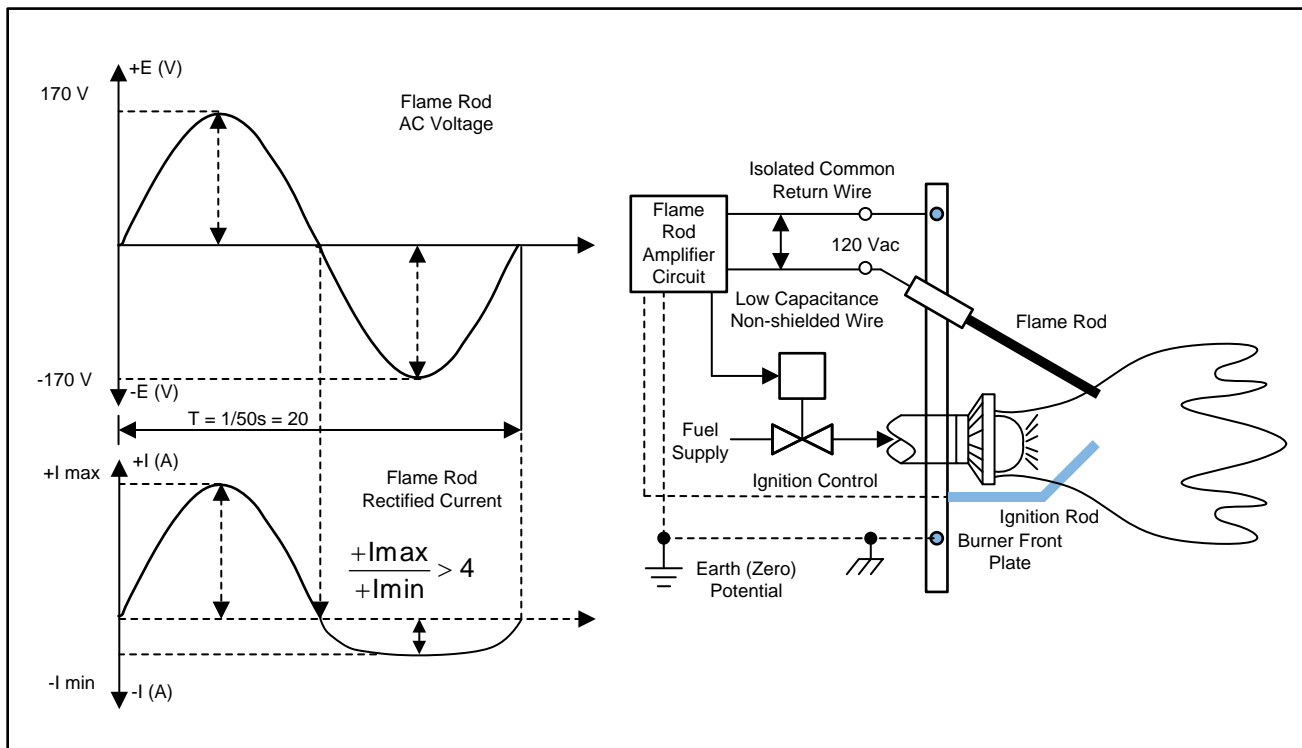


图 2. Flame Sensing Using Flame Rod

1.1 Key System Specifications

表 1. Key System Specifications

PARAMETER		SPECIFICATIONS			
		MIN	TYP	MAX	UNIT
Input supply voltage (V_{IN})	DC	10	24	33	V
	AC at 50 or 60	18	24	33	
Quiescent current (I_Q)		—	—	0.3	A
Output voltage (V_O)		105	120	140	V
Output current (I_O)		—	—	0.0015	A
Output load (R_L)					
Max cable capacitance 720 pF, assuming 22 AWG, 60 feet, 1 pair twisted cable 12 pF/ft		1	40	100	MΩ

表 1. Key System Specifications (continued)

PARAMETER		SPECIFICATIONS			
		MIN	TYP	MAX	UNIT
Performance	Initial accuracy	—	5	—	%
	THD	—	4	—	%
	Startup time at 10 V	—	—	100	ms

2 System Overview

2.1 Block Diagram

The power block can be divided into four sections (as shown in 图 3) for understanding system design calculations.

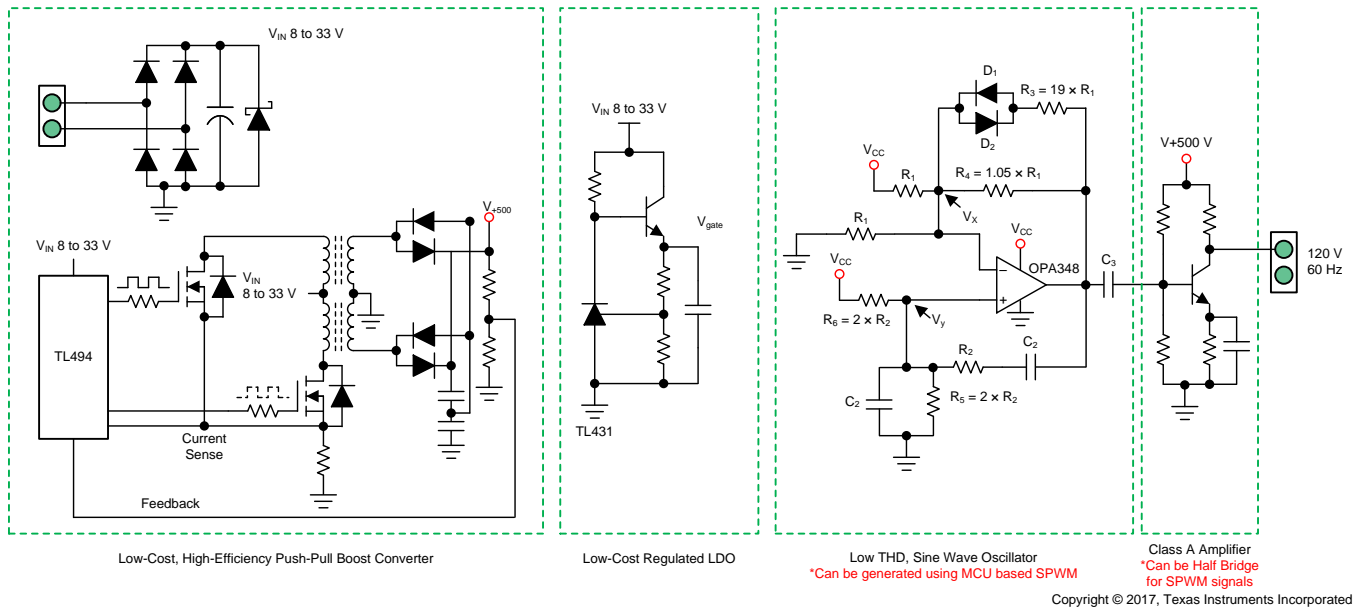
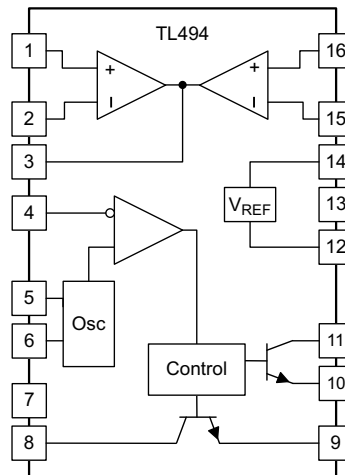


图 3. System Block Diagram

2.2 Highlighted Products

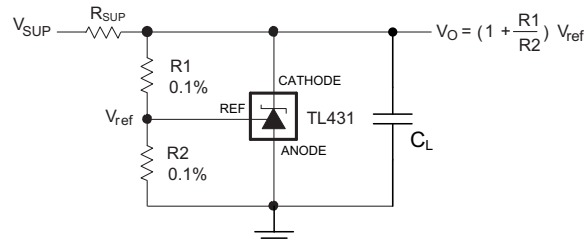
2.2.1 TL494

The TL494 device incorporates all the functions required in the construction of a control circuit for pulse width modulation (PWM) on a single chip. The TL494 device contains two error amplifiers, an on-chip adjustable oscillator, a dead-time control (DTC) comparator, a pulse-steering control flip-flop, a 5-V, 5%-precision regulator, and output control circuits. The error amplifiers exhibit a common-mode voltage ranging from -0.3 V to $V_{CC} - 2\text{ V}$. The DTC comparator has a fixed offset that provides approximately 5% dead time. The uncommitted output transistors provide either common-emitter or emitter-follower output capability. The TL494 device provides for push-pull or single-ended output operation, which can be selected through the output-control function. The architecture of this device prohibits the possibility of either output being pulsed twice during push-pull operation. The TL494C device is characterized for operation from 0°C to 70°C . The TL494I device is characterized for operation from -40°C to 85°C .


图 4. TL494 Block Diagram

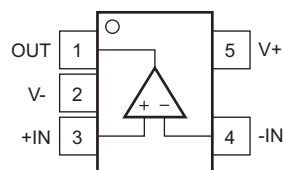
2.2.2 TL431

The TL431 device is a three-terminal adjustable shunt regulator. The output voltage can be set to any value between V_{REF} (approximately 2.5 V) and 36 V with two external resistors. These devices have a typical output impedance of 0.2 Ω . Active output circuitry provides a very sharp turnon characteristic, making these devices excellent replacements for Zener diodes in onboard regulation, adjustable power supplies, and switching power supplies.


图 5. TL431 Shunt Regulator

2.2.3 TLV171

The 36-V TLV171 device provides a low-power option for cost-conscious industrial systems requiring an electromagnetic interference (EMI)-hardened, low-noise, single-supply operational amplifier (op amp) that operates on supplies ranging from 2.7 V (± 1.35 V) to 36 V (± 18 V). The TLV171 provides low offset, drift, and quiescent current balanced with high bandwidth for the power. Input signals beyond the supply rails do not cause phase reversal. The TLV171 is stable with capacitive loads up to 200 pF. The input can operate 100 mV below the negative rail and within 2 V of the top rail during normal operation.


图 6. TLV171 Block Diagram

2.2.4 CSD19538Q3A

The CSD19538Q3A is NexFET™ power MOSFET with a drain-to-source voltage of 100 V, a low $R_{DS(on)}$ of 49 mΩ, and small footprint SON of 3.3 mm × 3.3 mm to achieve very low conduction losses and reduce board space.

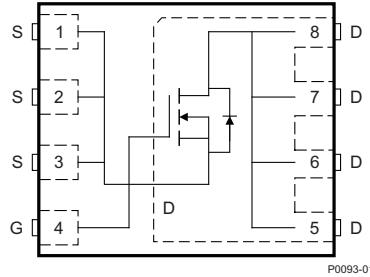
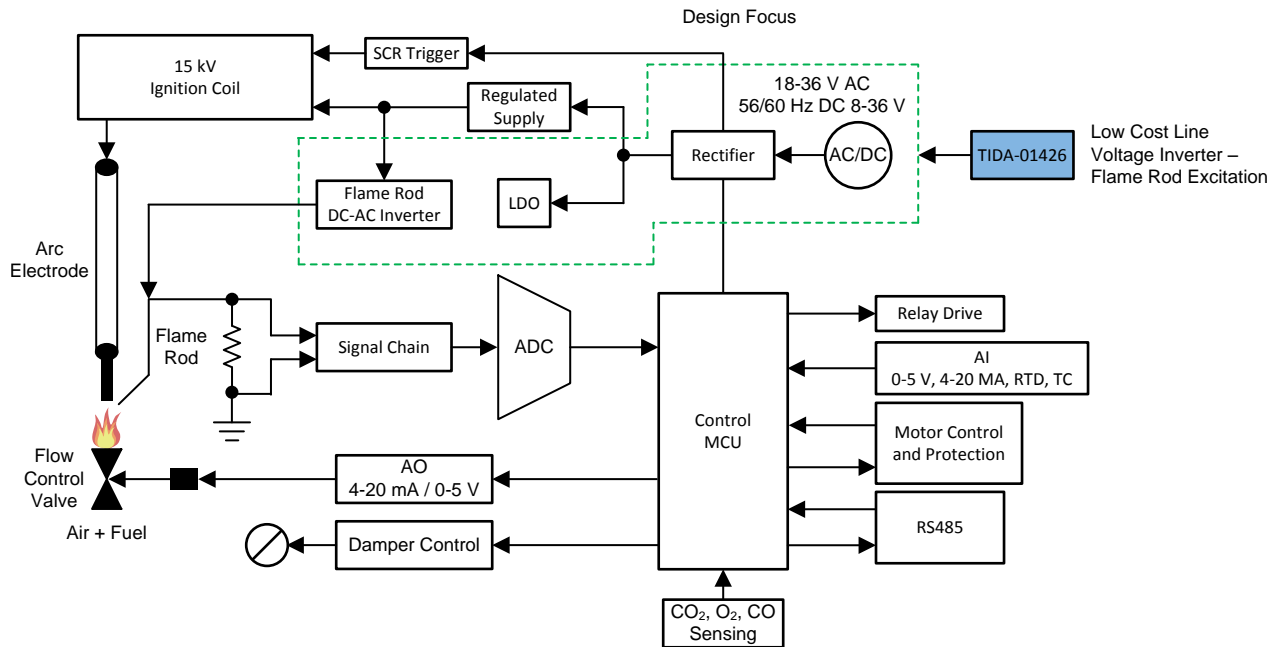


图 7. MOSFET CSD19538Q3A

2.3 System Design Theory

The TIDA-01426 design focuses on the design of a power supply targeted for flame rod excitation in burner control, as shown in 图 8. The supply needs to generate a low-voltage regulated supply for low-power peripherals and line supply voltage for flame rod excitation. Using the TL494 and TL431 devices generates the required low- and high-voltage supplies.



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图 8. Typical Electronics Control Board

2.3.1 Designing Push-Pull Converter

2.3.1.1 TL494 Calculations

To generate high DC bus voltage, push-pull topology is implemented in this reference design. Using flux swing in both polarities and high switching frequency makes it easy to design the small size magnetic transformer. TL494 integrated peripherals like an oscillator, dead-time controller, error amplifier, and PWM generator make it possible to design a low-cost, regulated output, push-pull converter.

2.3.1.1.1 Oscillator Calculations

The oscillator of the TL494 is set by R_t and C_t . To design a smaller magnetic transformer, a 100-kHz oscillating frequency is selected. For push-pull configuration with a C_t of 1 nF, the computed R_t value is 5k as shown in 公式 1. The closest standard value is 4.99k. In the schematic, R_6 and C_6 denotes R_t and C_t . For stable oscillations, a low-ppm resistor and COG capacitor are recommended.

$$R_T = \frac{1}{2 \times f_{OSC} \times C_T} = \frac{10^9}{2 \times 100000 \times 1} = 5 \text{ k} \quad (1)$$

2.3.1.1.2 Soft-Start and Dead-Time Calculations

The TL494 can be tailored for custom soft-start and dead time to prevent high in-rush current and cross conduction. As shown in 图 9, capacitor C_2 with R_6 applies a negative slop waveform, allowing the pulse width to increase slowly. Initially capacitor C_2 forces the DTC to follow an input of 5 V, which results in 100% dead time. Soft-start can be configured in multi of clock cycle as shown in 公式 2.

$$C_2 = \frac{100 \times \frac{1}{f_{SW}}}{R_6} = \frac{100 \times \frac{1}{100000}}{1000} = 1 \mu\text{F} \quad (2)$$

As the soft-start slope slowly decays, the potential due resistor divider R_6 and R_7 with an internal 0.1-V offset result into a tailored dead time. After soft-start, the voltage at the pin is a ratio of $R_6:R_7$ multiplied by V_{REF} . The value for dead time is computed based on the turnon and turnoff time of the MOSFET so that enough blanking is provided to prevent cross conduction. For this reference design, a blanking time of 500 ns is provided with resistor R_7 of 5k.

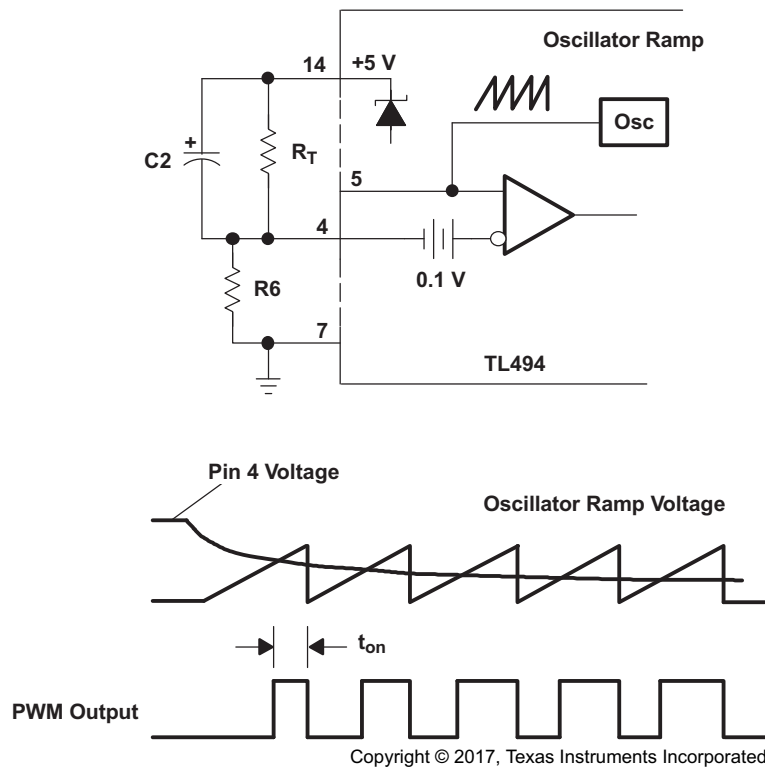


图 9. Soft-Start Circuit

2.3.1.1.3 Voltage Error Amplifier

A simple non-inverting error amplifier is implemented with one of the TL494 internal op amps. An internal reference of 5 V is divided to 2.5 using resistors R_{11} and R_{14} in board. 图 10 is shown with resistors R_3 and R_4 . The desired output is scaled to 2.5 V using resistors R_{10} and R_7 . The closed loop gain of the op amp ($= 101$) helps to maintain stable output. Resistors R_9 and R_4 are feedback resistors on board to get the desired closed loop gain.

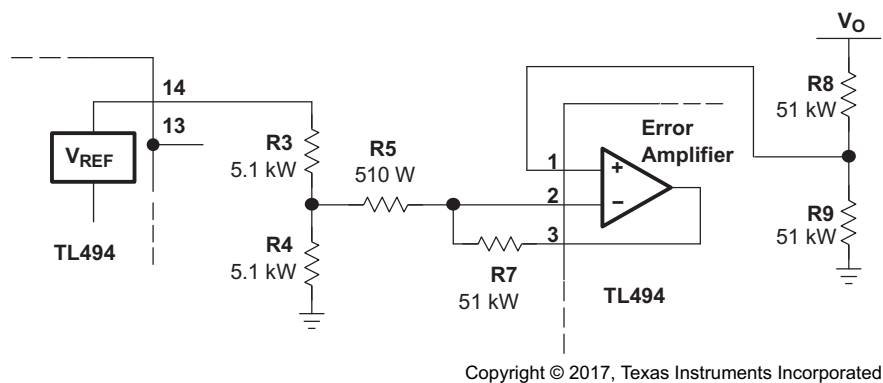
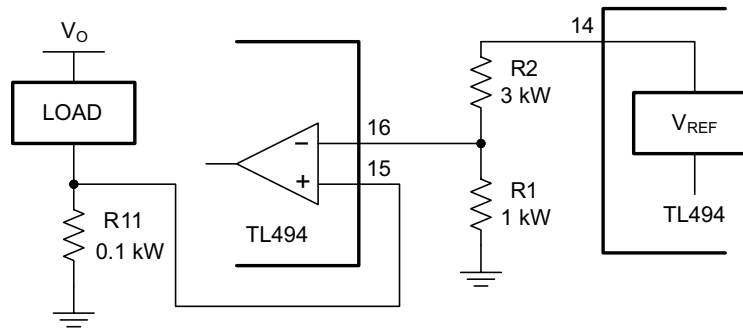


图 10. Feedback Error Amplifier

2.3.1.1.4 Overcurrent Protection

Overcurrent protection is implemented using one of the internal op amps of the TL494. A stable 1 V is applied to the negative terminal of the op amp using resistors R_{13} and R_{15} in the actual circuit. A current sense resistor R_{12} of $1\ \Omega$ is connected to the source pin of the MOSFET Q_1 and Q_2 . The circuit is limited to a peak current of 1 A once the voltage across sense resistor R_{12} increases to a 1-V reference.



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图 11. Current-Limiting Circuit

2.3.1.2 Magnetic Design

The objective for this application is to have a smaller footprint transformer. To achieve the same, this reference design has a 100-kHz switching frequency and a max duty cycle of 40%. In this application, Würth E13 core transformer is used. For a custom transformer design, the proper core material needs to be selected. N87, N88, N95, N96, and N97 are some standard core materials available from TDK Epcos for a switching frequency up to 500 kHz. N87 core can be selected which has saturation flux of 0.39 T at 100°C with core loss of 3.75 mW / mm³ at 100 kHz switching. This application uses a custom Würth Transformer. The design equations shown in 表 3 can be used for a custom transformer design. For a cost-sensitive application, a Toroid core can also be used. For ease of design, the maximum flux swing (B_m) can be limited to 0.2 T with current density (J) of 3 A/mm². The E13 core is selected to show design calculations.

表 2. E13 Core Calculations

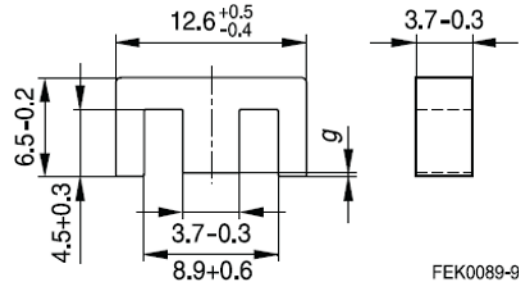
SR NO	PARAMETER	VALUE	UNIT
1	Cross sectional area (A_c)	12.4	mm ²
2	Window area (A_w)	$\left(\frac{8.9 - 3.7}{2} - 0.3\right) \times (4.5 - 0.3) = 9.66$ where 0.3 is for bobbin clearance	mm ²
3	Area product (A_p)	$A_c \times A_w = 82.58$	mm ⁴
4	Nominal inductance (A_l)	850	nH

E 13/7/4 (EF 12.6)

Core

B66305

- To IEC 61246
- For miniature transformers
- Available with SMD coil former
- E cores with high permeability for common-mode chokes and broadband applications
- Delivery mode: single units



Magnetic characteristics (per set)

$\Sigma l/A = 2.39 \text{ mm}^{-1}$

$l_e = 29.6 \text{ mm}$

$A_e = 12.4 \text{ mm}^2$

$A_{\text{min}} = 12.2 \text{ mm}^2$

$V_e = 367 \text{ mm}^3$

Approx. weight 2 g/set

Ungapped

Material	A_L value nH	μ_e	P_V W/set	Ordering code
N30	1000 +30/-20%	1900		B66305G0000X130
T46	3600 ±30%	6839		B66305F0000X146
N27	800 +30/-20%	1510	< 0.40 (200 mT, 100 kHz, 100 °C)	B66305G0000X127
N87	850 +30/-20%	1620	< 0.20 (200 mT, 100 kHz, 100 °C)	B66305G0000X187

图 12. E13 Core Specification

表 3. Transformer Calculations

SR NO	PARAMETER	EQUATION	COMPUTED VALUE	SELECTED VALUE
1	Required area product	$A_p = \frac{(\sqrt{2} \times V_{DC} \times I_{DC}) \times \left(1 + \frac{1}{\eta}\right)}{4 \times k_w \times B_m \times f_s \times J}$ where $k_w = 0.4$, $\eta = 0.8$, $V_{DC} = 500$ V, and $I_{DC} = 2$ mA	33.14 mm ⁴	Area product computed as shown in 表 2 is greater
2	Primary turns	$N_1 = \frac{V_{MIN}}{4 \times B_m \times f_s \times A_c}$ where A_c is the cross section of the core	10	10
3	Turns ratio	$n = \frac{V_{DC}}{2 \times D_{MAX} \times V_{MIN}}$ where $D_{MAX} = 0.4$	62.5	63
4	Secondary turns	$N_2 = n \times N_1$	630	630
5	Secondary RMS current	$I_2 = \sqrt{D_{MAX}} \times I_{DC}$	1.43 mA	—
6	Primary RMS current	$I_1 = n \times I_2$	90.5 mA	—
7	Cross section area of primary wire	$a_1 = \frac{I_1}{J}$	0.026 mm ²	36 SWG 0.02927 mm ²
8	Cross sectional area of secondary wire	$a_2 = \frac{I_2}{J}$	0.0004 mm ²	45 SWG 0.003973 mm ²
9	Total winding area	$\sum_{i=1}^2 a_i N_i = (2 \times N_1 \times a_1) + (N_2 \times a_2)$	3.08 mm ²	—
10	Utilization factor	$\left(\frac{\text{Total Winding Area}}{\text{Window Area } A_w} \right) \times 100$	31.88 %	Value < 40 %

Inductors can be added in series with output diodes and capacitors to limit ripple current.

2.3.1.3 MOSFET Drive and Losses

The fast switching speed, low drop voltage, and high input impedance of MOSFETs make them suitable for push-pull switching. The TI NexFET CSD19538Q3A with low drain-to-source channel resistance is selected for push-pull drive. The MOSFET is driven using an external totem pole transistor for a better drive capability.

2.3.1.3.1 Conduction Losses

The MOSFET gate drive is driven through the totem pole circuit as shown in 图 13.

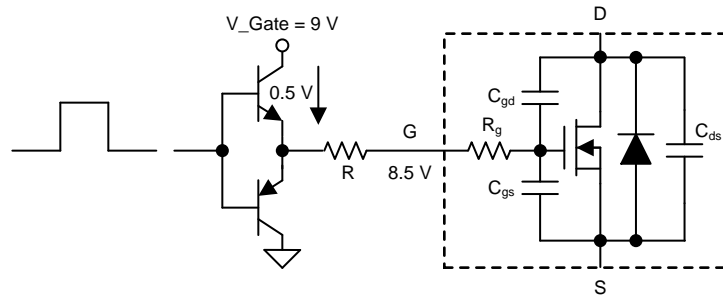


图 13. MOSFET Totem Pole Drive

During high pulse, the NPN transistor conducts resulting in a gate drive voltage of 8.5 V due to a 0.5-V drop across the collector emitter. From the MOSFET datasheet, the typical $R_{DS(on)}$ for a 8-V gate-to-source voltage is 50 mΩ.

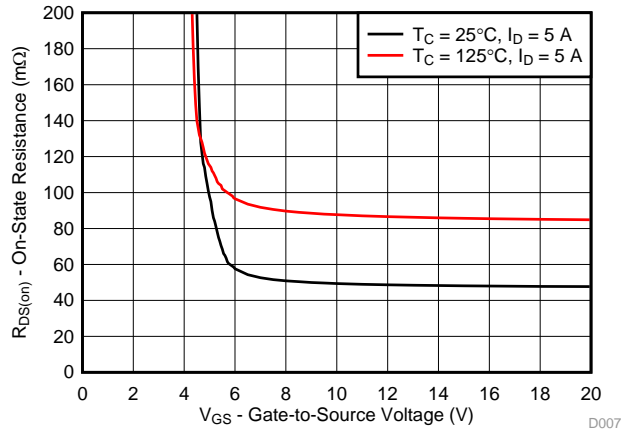


图 14. MOSFET On-State Resistance

Power loss during conduction phase is computed as shown in 公式 3.

$$P_{cond} = \frac{1}{T} \int_0^{ton} (n \times I_0)^2 \times R_{DS(on)} dt = \frac{1}{T} (n \times I_0)^2 \times R_{DS(on)} \times ton = (n \times I_0)^2 \times R_{DS(on)} dt \times D = 317 \mu W \quad (3)$$

2.3.1.3.2 Gate Drive Power Loss

During turnon, the gate-to-source capacitance (C_{gs}) charges through resistor $R + R_g$. The current waveform is exponential decay. During this period there is power loss across the N-channel transistor. Q_{gs} is obtained from the MOSFET datasheet as shown in 表 4.

表 4. Electrical Characteristics⁽¹⁾

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
STATIC CHARACTERISTICS						
BV_{DSS}	Drain-to-source voltage	$V_{GS} = 0\text{ V}, I_D = 250\ \mu\text{A}$	100.0	—	—	V
I_{DSS}	Drain-to-source leakage current	$V_{GS} = 0\text{ V}, V_{DS} = 80\text{ V}$	—	—	1.0	μA
I_{GSS}	Gate-to-source leakage current	$V_{DS} = 0\text{ V}, V_{GS} = 20\text{ V}$	—	—	100.0	nA
$V_{GS(th)}$	Gate-to-source threshold voltage	$V_{DS} = V_{GS}, I_D = 250\ \mu\text{A}$	2.8	3.2	3.8	V
$R_{DS(on)}$	Drain-to-source on resistance	$V_{GS} = 6\text{ V}, I_D = 5\text{ A}$	—	58.0	72.0	m Ω
		$V_{GS} = 10\text{ V}, I_D = 5\text{ A}$	—	49.0	59.0	
g_{fs}	Transconductance	$V_{DS} = 10\text{ V}, I_D = 5\text{ A}$	—	6.1	—	S
DYNAMIC CHARACTERISTICS						
C_{iss}	Input capacitance	$V_{GS} = 0\text{ V}, V_{DS} = 50\text{ V}, f = 1\text{ MHz}$	—	349.0	454.0	pF
C_{oss}	Output capacitance		—	69.0	90.0	pF
C_{rss}	Reverse transfer capacitance		—	12.6	16.4	pF
R_G	Series gate resistance	—	—	4.6	9.2	Ω
Q_g	Gate charge total (10 V)	$V_{DS} = 50\text{ V}, I_D = 5\text{ A}$	—	4.3	—	nC
Q_{gd}	Gate charge gate-to-drain		—	0.8	—	nC
Q_{gs}	Gate charge gate-to-source		—	1.6	—	nC
$Q_{g(th)}$	Gate charge at V_{th}		—	1.0	—	nC
Q_{oss}	Output charge	$V_{DS} = 50\text{ V}, V_{GS} = 0\text{ V}$	—	12.3	—	nC
$t_{d(on)}$	Turnon delay time	$V_{DS} = 50\text{ V}, V_{GS} = 10\text{ V}, I_{DS} = 5\text{ A}, R_G = 0\ \Omega$	—	5.0	—	ns
t_r	Rise time		—	3.0	—	ns
$t_{d(off)}$	Turnoff delay time		—	7.0	—	ns
t_f	Fall time		—	2.0	—	ns
DIODE CHARACTERISTICS						
V_{SD}	Diode forward voltage	$I_{SD} = 5\text{ A}, V_{GS} = 0\text{ V}$	—	0.85	1	V
Q_{rr}	Reverse recovery charge	$V_{DS} = 50\text{ V}, I_F = 5\text{ A}, di/dt = 300\text{ A}/\mu\text{s}$	—	94.00	—	nC
t_{rr}	Reverse recovery time		—	32.00	—	ns

⁽¹⁾ $T_A = 25^\circ\text{C}$

Power lost due to gate switching is computed as shown in 公式 4.

$$P_{GATE} = V_{GS} \times Q_{GS} \times f_{SW} = 8.5 \times 1.6 \times 10^{-9} \times 100000 = 1.36\text{ mW} \quad (4)$$

2.3.1.3.3 MOSFET Switching Losses

During turnon and turnoff, the gate voltage rises slowly as the input capacitance charges, this results in switching loss across MOSFET. These losses can be computed independently for turn on and turn off by computing timing of each phase. As shown in 图 15 and 图 16, during turnon initially the input capacitance charges until the gate potential reaches the gate threshold voltage. After reaching the threshold, the drain current starts to increase until the gate voltage reaches Miller voltage. After reaching Miller voltage, the drain-to-source voltage falls as the gate-to-drain capacitance charges. Switching losses are in the region between the threshold voltage to Miller voltage and from the Miller voltage to the fall of the drain-to-source voltage.

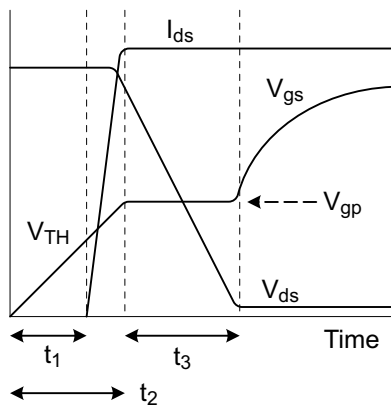


图 15. MOSFET Turnon Characteristics

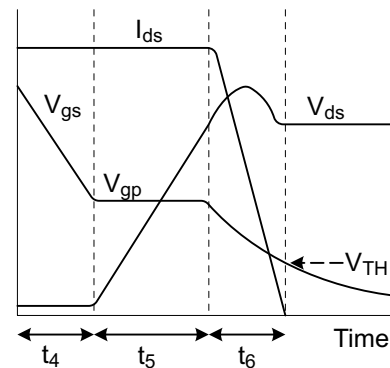


图 16. MOSFET Turnoff Characteristics

To compute the timings, the gate threshold voltage and plateau voltage need to be computed. From the MOSFET datasheet, gate voltage is computed using a two-point equation (see 图 17 and 公式 5).

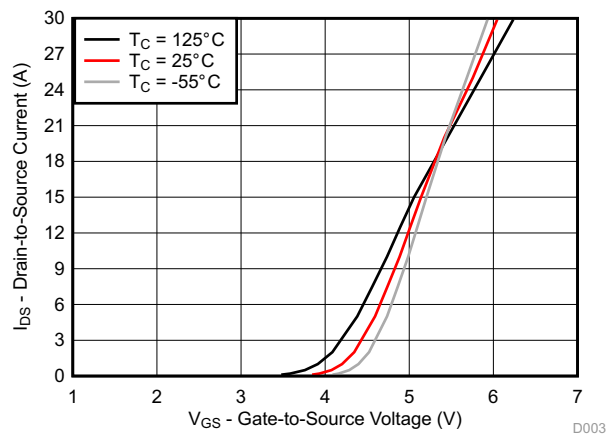


图 17. MOSFET Transfer Characteristics

$$V_{TH} = \frac{V_{GS1} \times \sqrt{I_{D2}} - V_{GS2} \times \sqrt{I_{D1}}}{\sqrt{I_{D2}} - \sqrt{I_{D1}}} = \frac{4.5 \times \sqrt{28} - 6 \times \sqrt{3}}{\sqrt{28} - \sqrt{3}} = 3.77 \text{ V} \tag{5}$$

The Miller voltage is computed as shown in 公式 6.

$$V_P = V_{TH} + \sqrt{\frac{I_1}{K}} = 3.77 + \sqrt{\frac{0.07968}{I_{D1}}} = 3.77 + \sqrt{\frac{0.0905}{3}} = 4 \text{ V} \tag{6}$$

With the gate threshold and Miller voltage computed, turnon timings t_1 , t_2 , and t_3 are shown in 公式 7, 公式 8, and 公式 9, respectively.

$$t_1 = (R_g + R_{ext}) \times C_{iss} \times \ln \left(\frac{1}{1 - \left(\frac{V_{TH}}{V_{GS}} \right)} \right) = (4.6 + 4.7) \times 349 \text{ pF} \times \ln \left(\frac{1}{1 - \left(\frac{1}{1 - \left(\frac{3.77}{8.5} \right)} \right)} \right) = 1.9 \text{ ns} \quad (7)$$

$$t_2 = (R_g + R_{ext}) \times C_{iss} \times \ln \left(\frac{1}{1 - \left(\frac{V_P}{V_{GS}} \right)} \right) = (4.6 + 4.7) \times 349 \text{ pF} \times \ln \left(\frac{1}{1 - \left(\frac{4}{8.5} \right)} \right) = 1.98 \text{ ns} \quad (8)$$

$$t_3 = (R_g + R_{ext}) \times C_{GD} \times \frac{V_{MIN}}{(V_{GS} - V_{GP})} = (4.6 + 4.7) \times 12.6 \text{ pF} \times \frac{12}{(8.5 - 3.89)} = 305 \text{ ps} \quad (9)$$

With timings t_1 , t_2 , and t_3 computed, power loss during turnon time is calculated using 公式 10.

$$P_{ton} = \left(V_{IN} \times \frac{(n \times I_0)}{2} \times (t_2 - t_1) \times f_{SW} \right) + \left(n \times I_0 \times \frac{(V_{IN})}{2} \times t_3 \times f_{SW} \right) = 18.4 \text{ } \mu\text{W} \quad (10)$$

Similarly, the turnoff timings t_4 , t_5 , t_6 , and turnoff loss is computed as shown in 公式 11, 公式 12, and 公式 13.

$$t_4 = (R_g + R_{ext}) \times C_{iss} \times \ln \left(\frac{V_{GS}}{V_P} \right) = (4.6 + 4.7) \times 349 \text{ pF} \times \ln \left(\frac{12}{4} \right) = 3.65 \text{ ns} \quad (11)$$

$$t_5 = (R_g + R_{ext}) \times C_{GD} \times \frac{V_{DS}}{V_P} = (4.6 + 4.7) \times 12.6 \text{ pF} \times \frac{12}{4} = 361 \text{ ps} \quad (12)$$

$$t_6 = (R_g + R_{ext}) \times C_{iss} \times \ln \left(\frac{V_P}{V_{TH}} \right) = (4.6 + 4.7) \times 349 \text{ pF} \times \ln \left(\frac{4}{3.77} \right) = 1001 \text{ ps} \quad (13)$$

With timings t_4 , t_5 , and t_6 computed, power loss during turnoff time is calculated using 公式 14.

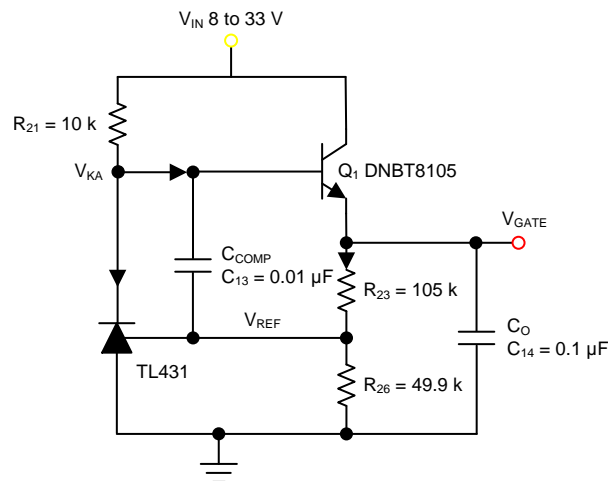
$$P_{toff} = \left(n \times I_0 \times \frac{(V_{IN})}{2} \times t_5 \times f_{SW} \right) + \left(V_{IN} \times \frac{(n \times I_0)}{2} \times t_6 \times f_{SW} \right) = 22.1 \text{ } \mu\text{W} \quad (14)$$

The total power loss in MOSFET is calculated using 公式 15:

$$P_T = P_{cond} + P_{GATE} + P_{ton} + P_{toff} = 1.7 \text{ mW} \quad (15)$$

2.3.1.4 LDO Using TL431

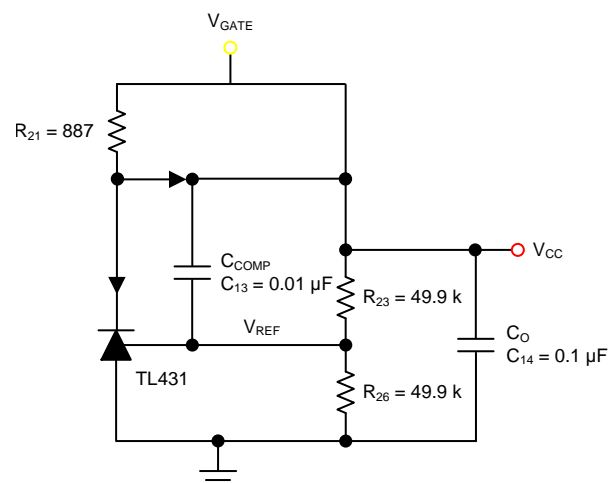
The regulated gate drive supply and peripheral supply are generated using a discrete LDO designed with the TL431. This peripheral supply can be used to power up the MCU, op amp, and other peripherals in a burner control system. In this reference design, the LDO powers up the sine wave oscillator. The components in the gate drive supply as shown in 图 18 is computed as per Section 2.2.2.1 of the [TIDA-01065 design guide](#) with a feedback current of 50 μA . The capacitor C_{13} is introduced for stability by adding zero in the feedback loop. This capacitor improves the phase margin and reduces oscillation in output.



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图 18. Gate Voltage Supply

The peripheral LDO is designed with an output current of 1 mA and 5 V. The values of discrete components as shown in 图 19 are computed as per Section 2.2.2.1 of the [TIDA-01065 design guide](#) with a feedback current of 50 μA . The capacitor C_{13} is introduced for stability by adding zero in the feedback loop. This capacitor improves the phase margin and reduces oscillation in output.

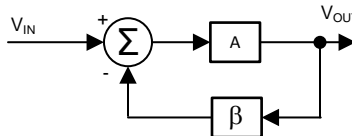


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图 19. Peripheral Supply

2.3.1.5 Sine Wave Oscillator

In this reference design, a sine wave oscillator is used to generate a 50-Hz line signal by using a low THD+noise op amp. With this approach, it is possible to produce very low distorted output. As shown in [Figure 20](#), the oscillator must satisfy the criteria for a closed loop positive feedback for the circuit to oscillate. Due to positive feedback, the denominator value becomes zero, resulting in instability known as Barkhausen Criterion. In unstable mode, the output of circuit tends to infinity due to the limitation of the power rail in circuit output will saturate to rail supply. For active devices, the gain of the circuit changes as output approaches the supply rail. This results in a change of value A and forces Aβ away from the singularity. Due to this change, trajectory towards power rail slows and eventually halts.



$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta}$$

if $A\beta = -1 = 1 \angle -180$

图 20. Oscillator Control Loop

At this point, any one of these three possible conditions can occur:

- Nonlinearity in saturation or a cutoff region may result to become stable and latch at a particular output
- Initial change may cause the active device to be saturated or cut off for a long period before becoming linear and then moving to an opposite rail
- The circuit stays linear and reverses polarity to an opposite rail

The second condition results in a distorted output and is usually preferred for generating quasi square wave signals, while the third conditions produces sine wave output. The gain and phase of the circuit play a critical role for designing a sine wave oscillator. For an op-amp based circuit, the phase margin of the op amp must be negligible so that the closed loop positive feedback archives $\angle -180$ phase shift at oscillating frequency. Considering these conditions, the closed loop gain, phase shift, THD distortion, and slew rate are some key parameters for selecting an op amp to design sine wave oscillators.

This reference design uses a single-supply Wein bridge oscillator. The classic Wein bridge oscillator has both positive and negative feedback. This helps in getting a very low distorted output. For analysis, consider the circuit as shown in [Figure 21](#). The circuit operating can be modeled as a non-inverting amplifier.

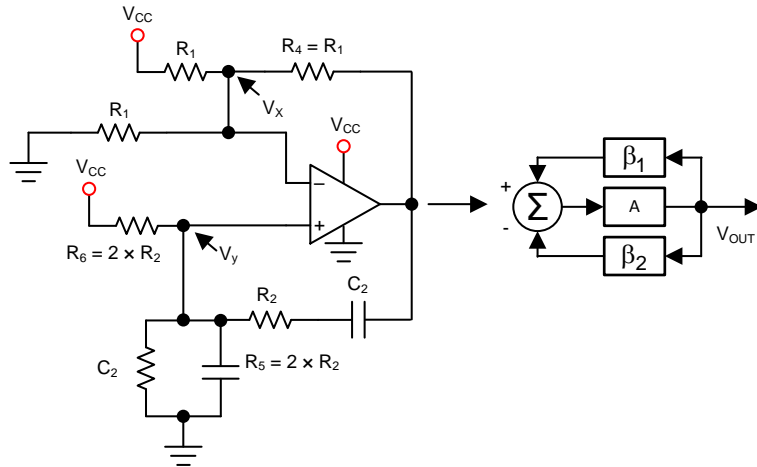


图 21. Sine Wave Oscillator for Op Amp

Voltage at the positive terminal of the op amp is given using 公式 16.

$$V_y = V_O \times \left(\frac{sR_2C_2}{1 + 3sR_2C_2 - (sR_2C_2)^2} \right) \quad (16)$$

A simple form of 公式 16 in a frequency parameter is given using 公式 17.

$$\beta = \frac{V_y}{V_O} = \left(\frac{1}{3 + j \left(\frac{f}{f_{R_2C_2}} - \frac{f_{R_2C_2}}{f} \right)} \right), \text{ where } f_{R_2C_2} = \frac{1}{2\pi R_2C_2} \quad (17)$$

From a classic non-inverting amplifier, the closed loop gain equation ignoring the dominant pole effect at a low frequency is given using 公式 18.

$$V_O = V_y \times \left(1 + \frac{R_4}{R_1} \right) \quad (18)$$

As a result, the forward gain is found using 公式 19.

$$A = \frac{V_O}{V_y} = \left(1 + \frac{R_4}{R_1} \right) \quad (19)$$

The total loop gain is given using 公式 20.

$$T(jf) = A\beta = \frac{\left(1 + \frac{R_4}{R_1} \right)}{\left(3 + j \left(\frac{f}{f_{R_2C_2}} - \frac{f_{R_2C_2}}{f} \right) \right)} \quad (20)$$

These equations imply system response of bandpass filter, at higher and lower frequency it approaches to zero and at peak frequency of $f = f_{R_2C_2}$, the total loop gain reduces to:

$$t_{(jf_{R_2C_2})} = \frac{\left(1 + \frac{R_4}{R_1} \right)}{3} \quad (21)$$

The magnitude of the total loop gain has three possibilities:

- $T(jf_{R_2C_2}) < 1$: The pole pair lies in the left half of the complex plane, resulting in an exponentially decaying signal.
- $T(jf_{R_2C_2}) > 1$: This condition results in unstable operation, resulting in oscillation of growing amplitude. The pole pair lies on the right half of a complex plane. The oscillation builds up until the op amp saturates to the power rail. This condition results in a distorted output.
- $T(jf_{R_2C_2}) = 1$: This condition results in neutral stability. The pole pair lies exactly on an imaginary axis of the complex plane. It satisfies the Barkhausen criterion of the loop gain of unity and a phase shift of 360° . The output is sinusoidal with very low distortion. For this condition, the R_4/R_1 ratio needs to satisfy a magnitude of 2.

Due to the drift of active and passive devices, the total loop gain does not maintain a magnitude of value 1, so modify the circuit as shown in 图 22 to achieve automatic gain control (AGC). At initial startup condition, diodes D_1 , D_2 , and R_3 result into condition $T(jf_{R2C2}) > 1$, resulting into oscillations quickly building up. After the oscillation has built up, the gain stabilizes to match the Barkhausen criteria due to effective resistors $R3$ and $R4$, which are in parallel to achieve a ratio close to a magnitude of 2.

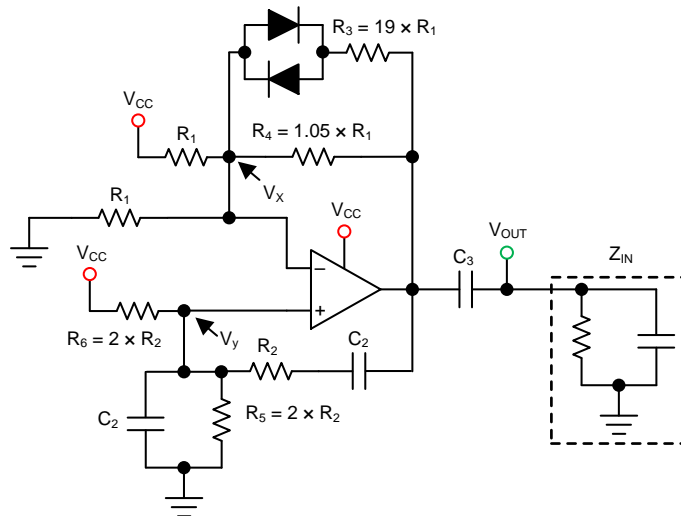


图 22. Practical Op Amp Oscillator

Select an op amp that has very low distortion for oscillating frequency, low noise, and enough of a slew rate to achieve sustain oscillation. The closed loop bandwidth needs to be greater than $270 f_{OSC}$. Therefore, for a 50-Hz f_{OSC} signal, the sine wave oscillator needs a closed-loop bandwidth greater than 13.5 kHz and a slew rate of $> 2\pi f_{OSC} V_O$. Selecting TLV171 from the device datasheet gets a unity gain bandwidth of 3 MHz and a typical open loop gain of 130 dB.

表 5. TLV171 Electrical Characteristic

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
OFFSET VOLTAGE					
V_{OS} Input offset voltage	$T_A = 25^\circ\text{C}$	—	0.75	± 2.7	mV
	$T_A = -40^\circ\text{C}$ to $+125^\circ\text{C}$	—	—	± 3.0	
dV_{OS}/dT Input offset voltage drift	$T_A = -40^\circ\text{C}$ to $+125^\circ\text{C}$	—	1	—	$\mu\text{V}/^\circ\text{C}$
PSRR Input offset voltage vs power supply	$V_S = 4\text{ V}$ to 36 V , $T_A = -40^\circ\text{C}$ to $+125^\circ\text{C}$	90	105	—	dB
INPUT BIAS CURRENT					
I_B Input bias current	—	—	± 10	—	pA
I_{OS} Input offset current	—	—	± 4	—	pA
NOISE					
Input voltage noise	$f = 0.1\text{ Hz}$ to 10 Hz	—	3	—	μV_{PP}
e_n Input voltage noise density	$f = 100\text{ Hz}$	—	27	—	$\text{nV}/\sqrt{\text{Hz}}$
	$f = 1\text{ kHz}$	—	16	—	
INPUT VOLTAGE					
V_{CM} Common-mode voltage range	—	$(V-) - 0.1$	—	$(V+) - 2$	V
CMRR Common-mode rejection ratio	$V_S = \pm 18\text{ V}$, $(V-) - 0.1\text{ V} < V_{CM} < (V+) - 2\text{ V}$, $T_A = -40^\circ\text{C}$ to $+125^\circ\text{C}$	94	105	—	dB
INPUT IMPEDANCE					
Differential	—	—	$100 \parallel 3$	—	$\text{M}\Omega \parallel \text{pF}$
Common-mode	—	—	$6 \parallel 3$	—	$10^{12}\ \Omega \parallel \text{pF}$

表 5. TLV171 Electrical Characteristic (continued)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
OPEN-LOOP GAIN						
A_{OL}	Open-loop voltage gain	$V_S = 36\text{ V}$, $(V_-) + 0.35\text{ V} < V_O < (V_+) - 0.35\text{ V}$, $T_A = -40^\circ\text{C to } +125^\circ\text{C}$	94	130	—	dB
FREQUENCY RESPONSE						
GBP	Gain bandwidth product	—	—	3.0	—	MHz
SR	Slew rate	$G = +1$	—	1.5	—	V/ μs
t_s	Settling time	To 0.1%, $V_S = \pm 18\text{ V}$, $G = +1$, 10-V step	—	6	—	μs
		To 0.01% (12 bits), $V_S = \pm 18\text{ V}$, $G = +1$, 10-V step	—	10	—	
	Overload recovery time	$V_{IN} \times \text{gain} > V_S$	—	2	—	μs
THD+N	Total harmonic distortion + noise	$G = +1$, $f = 1\text{ kHz}$, $V_O = 3\text{ V}_{RMS}$	—	0.0002%	—	—

As a result, the dominant pole frequency of the TLV171 is given using [公式 22](#).

$$f_{\text{dom}} = \frac{f_{\text{unity}}}{10^{20}} = \frac{130}{10^{20}} = 0.948\text{ Hz} \quad (22)$$

The closed loop AC gain for a non-inverting topology with a feedback factor of 1/3 at a frequency of 15 kHz is given using [公式 23](#).

$$A_{cl} = \frac{\frac{A_{DC_OPEN}}{1 + \beta \times A_{DC_OPEN}}}{\sqrt{1 + \frac{f^2}{f_{\text{dom}}^2} \frac{1}{(1 + \beta A_{DC_OPEN})^2}}} = \frac{\frac{3162277}{1 + 0.33 \times 3162277}}{\sqrt{1 + \left(\frac{15000^2}{0.948^2}\right) \times \left(\frac{1}{(1 + 0.33 \times 3162277)^2}\right)}} = 3.029 \quad (23)$$

So the TLV171 meets approximately a closed loop gain of 3. Calculate the phase margin error using [公式 24](#) to get a phase error of 0.003°.

$$\phi = 90^\circ - \left(\tan^{-1} \frac{f}{f_{\text{dom}}} \right) = 0.003^\circ \quad (24)$$

From the slew rate requirement, considering an output voltage of 4 V and a 50-Hz f_{OSC} slew rate needs to be greater than 1.25 mV/ μs (ignoring asymmetric slew rate error in non-inverting mode due to a common-mode parasitic).

$$SR > 2\pi \times f_{\text{OSC}} \times V_O \times 10^{-6} = 2\pi \times f_{\text{OSC}} \times V_O \times 10^{-6} > 1.25 \frac{\text{mV}}{\mu\text{s}} \quad (25)$$

By cross verifying with the TLV171 FPB, check that the slew rate satisfies the closed loop bandwidth requirement by using [公式 26](#).

$$FPB = \frac{SR \text{ in } \frac{\text{V}}{\mu\text{s}}}{2\pi \times V_O} = \frac{1.5 \times 10^6}{8\pi} = 59.7\text{ kHz} \quad (26)$$

2.3.1.6 High Gain Amplifier

To achieve a 120-V sine wave output, there needs to be an amplifier; this amplifier can be a topology like Class A, Class AB, and so on. To achieve the cost target, a Class A amplifier has been implemented in this reference design. Class AB can be implemented to achieve high efficiency and low distortion with a filter circuit. A Class A amplifier as shown in 图 23 operates in the linear operating region, due to which output distortion are low. In a Class A amplifier, additional quiescent current is required to bias the transistor in the operating region. Calculate the bias point to achieve linear output. This reference design uses the BSS127-S N-channel, high-voltage, low-cost MOSFET to design this Class A amplifier.

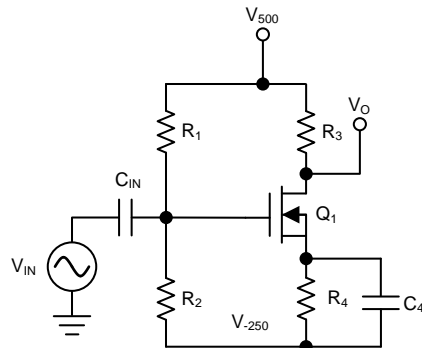
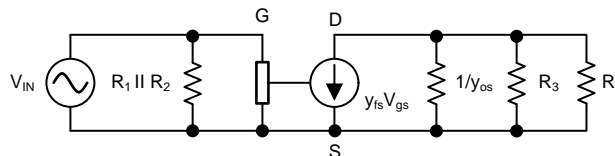


图 23. Class A Amplifier

Resistors R₁ and R₂ provide bias voltage to Q1. To calculate R₁ and R₂, first calculate the Q point of Q1 for the required gain. The AC equivalent of a circuit is as shown in 图 24.



y_{fs} : Forward trans conductance
 $1/y_{os}$: Output Admittance
 $A_v : y_{fs} \times (R_1 \parallel R_3 \parallel 1/y_{os})$

图 24. AC Equivalent Circuit

The drain current of the MOSFET is parabolic in nature, so the drain current is given using 公式 27.

$$I_{ds} = K \times (V_{GS\text{ON}} - V_{GS\text{OFF}})^2 \tag{27}$$

Solving 公式 27 for $V_{GS\text{ON}} = 10 \text{ V}$, $V_{GS\text{OFF}} = 3 \text{ V}$, and $I_{ds} = 16 \text{ mA}$ from the datasheet, compute K as shown in 公式 28.

Electrical Characteristics (@T_A = +25°C, unless otherwise specified.)

Characteristic	Symbol	Min	Typ	Max	Unit	Test Condition
OFF CHARACTERISTICS (Note 8)						
Drain-Source Breakdown Voltage	BV _{DSS}	600	—	—	V	V _{GS} = 0V, I _D = 250μA
Zero Gate Voltage Drain Current T _J = +25°C	I _{DSS}	—	—	0.1	μA	V _{DS} = 600V, V _{GS} = 0V
Gate-Body Leakage	I _{GSS}	—	—	±100	nA	V _{GS} = ±20V, V _{DS} = 0V
ON CHARACTERISTICS (Note 8)						
Gate Threshold Voltage	V _{GS(TH)}	3	—	4.5	V	V _{DS} = V _{GS} , I _D = 250μA
Static Drain-Source On-Resistance	R _{DS(ON)}	—	80	160	Ω	V _{GS} = 10V, I _D = 16mA
		—	95	190		V _{GS} = 5.0V, I _D = 16mA
Forward Transfer Admittance	Y _{fs}	—	76	—	mS	V _{DS} = 10V, I _D = 16mA
Diode Forward Voltage	V _{SD}	—	—	1.5	V	V _{GS} = 0V, I _S = 16mA
DYNAMIC CHARACTERISTICS (Note 9)						
Input Capacitance	C _{iss}	—	21.8	—	pF	V _{DS} = 25V, V _{GS} = 0V, f = 1.0MHz
Output Capacitance	C _{oss}	—	2.2	—		
Reverse Transfer Capacitance	C _{rss}	—	0.3	—		
Total Gate Charge	Q _g	—	1.08	—	nC	V _{GS} = 10V, V _{DD} = 300V, I _D = 0.01A
Gate-Source Charge	Q _{gs}	—	0.08	—		
Gate-Drain Charge	Q _{gd}	—	0.50	—		
Turn-On Delay Time	t _{D(ON)}	—	5.0	—	ns	V _{DD} = 300V, V _{GS} = 10V, R _{GEN} = 6Ω, I _D = 10mA
Turn-On Rise Time	t _R	—	7.2	—	ns	
Turn-Off Delay Time	t _{D(OFF)}	—	28.7	—	ns	
Turn-Off Fall Time	t _F	—	168	—	ns	
Reverse Recovery Time	t _{RR}	—	131	—	ns	V _R = 300V, I _F = 0.016A, di/dt = 100A/μs
Reverse Recovery Charge	Q _{RR}	—	32	—	nC	

- Notes:
- Device mounted on FR-4 PCB with minimum recommended pad layout, single sided.
 - Device mounted on 1" x 1" FR-4 PCB with high coverage 2 oz. Copper, single sided.
 - Repetitive rating, pulse width limited by junction temperature, 10μs pulse, duty cycle = 1%.
 - Short duration pulse test used to minimize self-heating effect.
 - Guaranteed by design. Not subject to production testing.

图 25. MOSFET Electrical Characteristics

$$k = \frac{dI_{dsq}}{dV_{GSq}} = 2 \times K \times (V_{GSq} - V_{GSOFF}) \quad (28)$$

The transconductance of the MOSFET is found by taking the derivative of the transfer function for the drain current at a bias point of the amplifier.

$$y_{fq} = \frac{dI_{dsq}}{dV_{GSq}} = 2 \times K \times (V_{GSq} - V_{GSOFF}) \quad (29)$$

Assuming the high load resistance and output admittance is sufficiently high, the impedance seen by the MOSFET is almost equal to R₃. For a good biasing point, it is good to bias the output at half of the supply rails. As a result, the drain resistance is given using 公式 30.

$$R_3 = 0.5 \times \frac{(V_{DD} + V_{SS})}{I_{DQ}} \quad (30)$$

By substituting R₃ and y_{fq} for the total gain in 公式 31:

$$A_{vq} = y_{fq} \times R_3 = 2 \times K \times (V_{GSq} - V_{GSOFF}) \times 0.5 \frac{(V_{DD} - V_{SS})}{I_{DQ}} \quad (31)$$

Rearranging the terms for I_{DQ} leads to 公式 32 :

$$I_{DQ} = \frac{2 \times K \times (V_{GSq} - V_{GSOFF}) \times 0.5 \times (V_{DD} - V_{SS})}{A_{vq}} \quad (32)$$

Solving 公式 27 and 公式 32 graphically with V_{dd} of 500 V, $V_{GSOFF} = 3$ V and a gain of 330, bias points V_{GSq} and I_{DQ} can be computed using interpret of two curves (see 图 26).

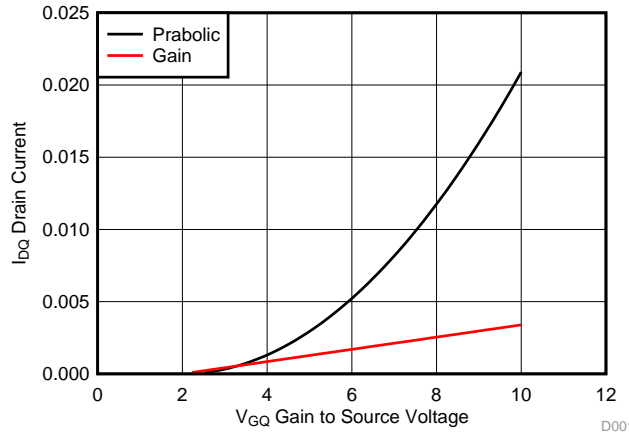


图 26. Bias Point Calculations

图 26 shows that the curve intercepts the x-axis at 3.3 V and the y-axis at 551 μ A. So the bias point for BSS127-S is $V_{GSQ} = 3.3$ V and $I_{DQ} = 551$ μ A.

Solving the equation with $I_{DQ} = 551$ μ A results in $R_3 = 442$ k. Selecting a closed standard value of 442 kV at the source can be set close to 0.09 times the supply rail. Computing for a V_{dd} of 500 V and $I_{DQ} = 551$ μ A results in $R_4 = 82$ k. Selecting the next standard resistor with a 5% tolerance we select 88.7k. With 88.7k and $I_{DQ} = 551$ μ A, the source voltage is 48.8 V. Adding the gate-to-source bias voltage, the gate voltage needs to be 52.1 V. Using voltage divider logic, R1 and R2 can be easily computed for a low-bias current. Assuming an R_2 of 2.2 M Ω and a supply rail V_{dd} of 500 V, the required resistance R_1 is 18 M Ω . The nearest standard value to select is 18 M Ω . Capacitance C_4 is a bypass capacitor for a higher AC gain value. To calculate C_4 , assume impedance by capacitance for a 50-Hz frequency as 0.1 times of R_4 .

$$X_C = 0.1 \times R_4 = 8.8 \text{ k} \quad (33)$$

By knowing the impedance of a capacitor at a specific frequency, it is easy to calculate capacitance using 公式 34.

$$C_4 = \frac{1}{2\pi f X_C} = 361 \text{ nF} \quad (34)$$

The next standard value selected is a 470-nF capacitor. Capacitance C_{in} is a high-pass-filter capacitor that blocks DC level from the oscillator output. The parallel resistance value of resistors R1 and R2 with C_{in} together form the high pass filter. By selecting a cutoff frequency of 5 Hz, compute C_{in} as per 公式 35.

$$C_{in} = \frac{1}{2\pi f_C \times 0.1 \times (R_1 \parallel R_2)} = 162 \text{ nF} \quad (35)$$

The next standard value of 220 nF is selected for the input filter capacitor.

3 Hardware, Testing Requirements, and Test Results

3.1 Hardware

Before powering up the TIDA-01426 board, verify for any components not populated as per the schematic. Check for power nodes and shock hazard symbols to avoid electric shocks as shown in 图 27.

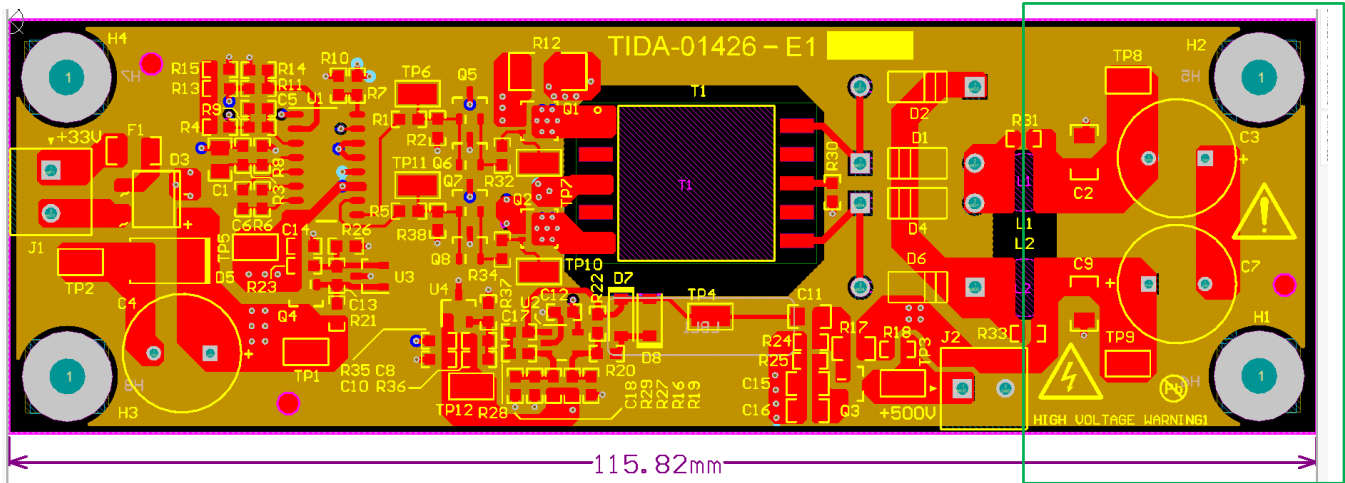


图 27. High-Voltage Section

3.1.1 Connectors

The interface board has two connectors as described in 表 6.

表 6. Input Output Connectors

CONNECTOR	DESCRIPTION	VOLTAGE
J1	Input voltage	12 to 36 V
J2	Output voltage	120 V _{RMS} , 60 Hz

3.1.2 Test Points

The required test points have been populated on the interface board to measure signals. See 表 7 for more details.

表 7. Test Points

TEST POINT NO	DESCRIPTION	VOLTAGE VALUE
TP1	Supply voltage	12 to 36 V
TP2, TP9	GND	0 V
TP5	Gate supply	8 V
TP12	Op amp supply	5 V
TP4	Sine wave oscillator	1.5 V _{RMS} , 60 Hz
TP3	Class A amplifier output	120 V _{RMS} , 60 Hz
TP6	Emitter 1 output	7-V, 100-kHz PWM
TP11	Emitter 2 output	7-V, 100-kHz PWM
TP7	Totem Pole 1 output	8-V, 100-kHz PWM
TP10	Totem Pole 2 output	8-V, 100-kHz PWM
TP8	Positive high voltage	500 V

The test setup is as shown in 图 28. Ensure the board is placed inside a safety enclosure to prevent any shock or short-circuit hazard.

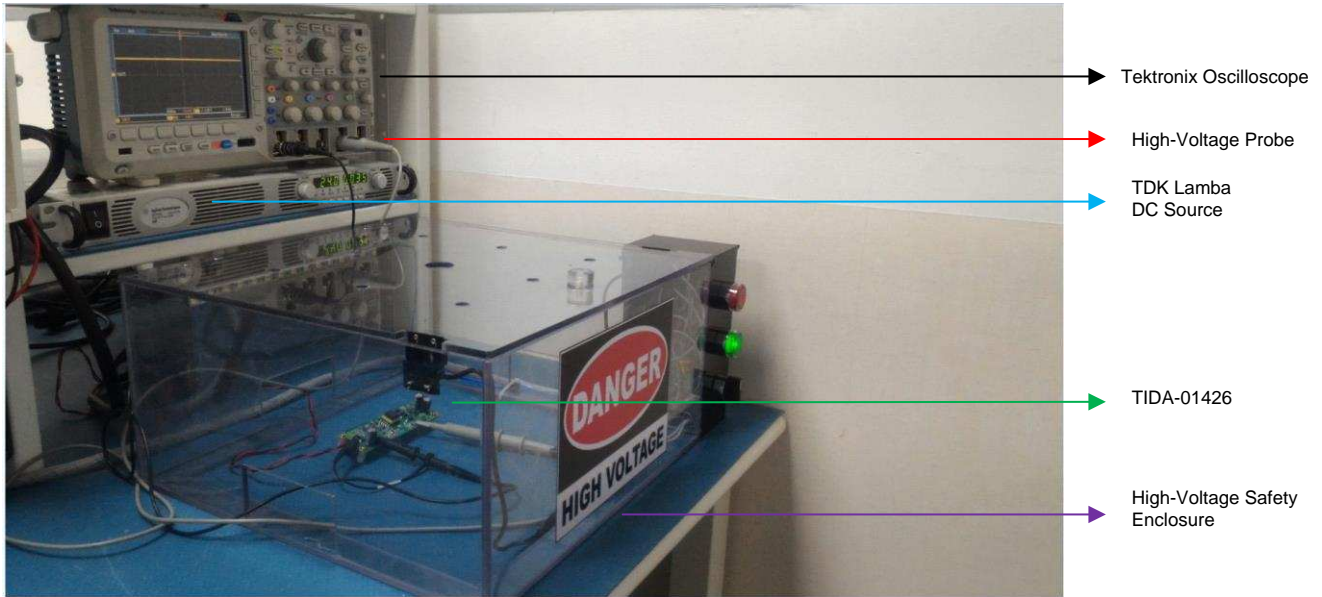


图 28. Test Setup

3.2 Testing and Results

3.2.1 Gate Supply

The following figures show the gate output voltage changes as the line voltage changes from the minimum supply to the maximum supply.

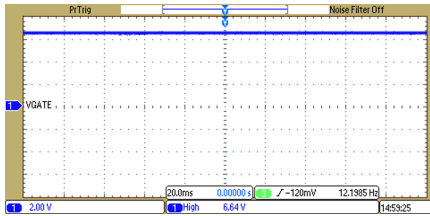


图 29. Gate Supply at 12 V_{IN}

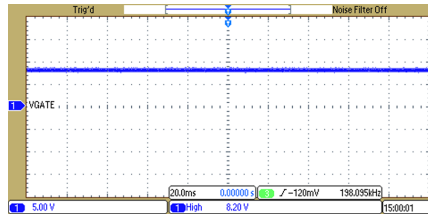


图 30. Gate Supply at 24 V_{IN}

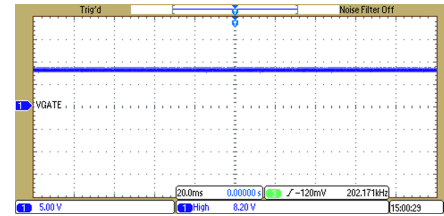


图 31. Gate Supply at 33 V_{IN}

3.2.2 LDO Supply

The following figures show the LDO output voltage as the line voltage changes from the minimum supply to the maximum supply.

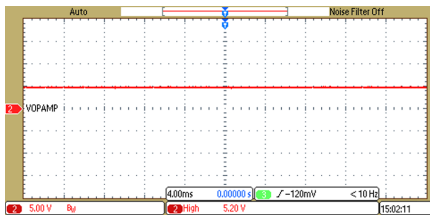


图 32. LDO Supply at 12 V_{IN}

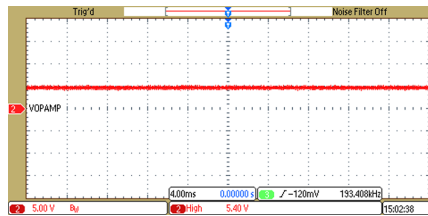


图 33. LDO Supply at 24 V_{IN}

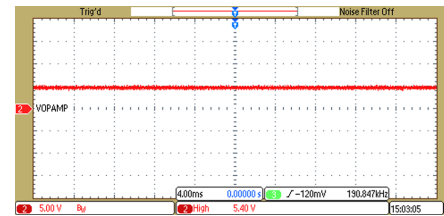


图 34. LDO Supply at 36 V_{IN}

3.2.3 Push-Pull Output

The start-up time for 500 V is tested at the lowest input supply. Yar gets a start-up time of 100 ms to achieve 55 ms as shown in 图 35.

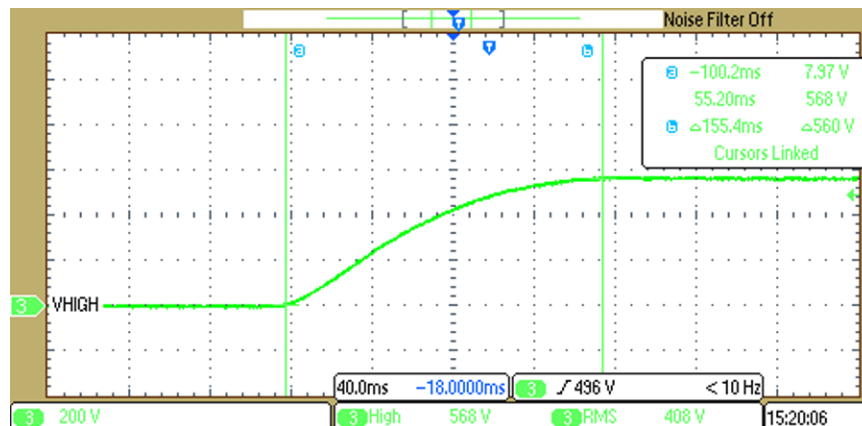


图 35. Start-up Time

3.2.4 Sensor Output

Sensor output is measured at a 24-V input, and the FFT plot is taken to verify harmonic content (see 图 36).

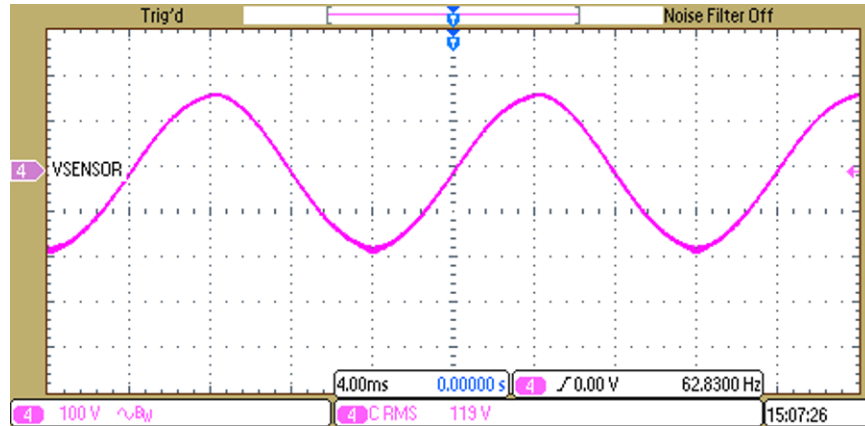


图 36. Sensor Output

As seen from 图 37, the peak is at 63 Hz with a 42-dB magnitude and harmonics with magnitudes of 7 dB, -18 dB, -12 dB, and -5 dB. The THD computed for an observed output is 1.8%.

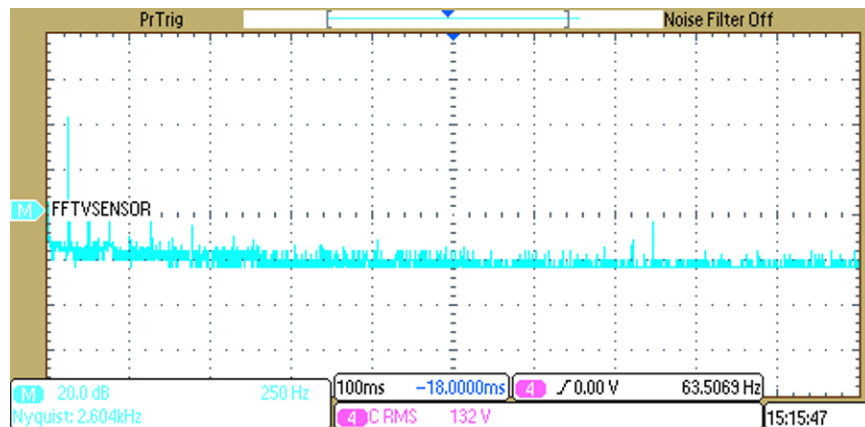


图 37. FFT Plot Sensor Output

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01426](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01426](#).

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01426](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01426](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01426](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01426](#).

5 Software Files

To download the software files, see the design files at [TIDA-01426](#).

6 Related Documentation

1. Texas Instruments, [Designing Switching Voltage Regulators With the TL494](#), TL494 Application Report (SLVA001)

6.1 商标

NexFET is a trademark of Texas Instruments.

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7 About the Authors

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