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# ***Low Cost Isolated Power Supply for Power-over-Ethernet (PoE) Applications***

***Reference Design***

# Low Cost Isolated Power Supply for Power-Over-Ethernet (PoE) Applications

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System Power

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## 1 Introduction

This document describes an easy-to-use, low-cost isolated power supply to be used in Power-over-Ethernet (PoE) powered devices (PD's) that is based on TI's TPS2370 PoE interface switch. PoE is an emerging new capability to deliver data and power to internet appliances over existing CAT-5 Ethernet cables. PoE is governed by the standards defined in IEEE802.3af. PoE is rapidly gaining in popularity with manufacturers and users of devices such as VoIP phones, wireless access points, security cameras and point-of-sale terminals.

Benefits of PoE systems include:

- Lower cost: external *wall wart* power supplies can be eliminated.
- Flexible access point location: wireless access points no longer need to be located in the vicinity of ac power sources or need to have ac power lines and outlets installed near them.
- Remote management capability: IP phones and WLAN access points can be powered up or down remotely. The remote host can determine how much power individual devices require and decide which devices should be turned on.
- Higher reliability: redundant power supplies can be used on the *switch* end to provide uninterrupted IP phone service.
- Worldwide compatibility: PoE creates a universal worldwide power connector.

In order to be compliant with the IEEE802.3af PoE standard, the powered device (PD) on the Ethernet line must be identified, classified, controlled at start up, and meet isolation requirements.

Per the isolation requirements of 802.3af, a PD shall provide electrical isolation between all power interface (PI) leads, external conductors, and frame ground. The isolation must meet the  $1500\text{-}V_{\text{RMS}}$  SELV requirements of sub-clause 6.2 of IEC 60950-1:2001.[2] A VoIP phone housed in a plastic case with no external connections or cables could meet this requirement. Another method to achieve isolation is to use a power converter that has a transformer with  $1500\text{-}V_{\text{RMS}}$  isolation and opto-isolated output voltage feedback. Electrical isolation is an attractive option for manufacturers of VoIP phones and WLAN access points that want to include additional Ethernet ports in their products to be used with downstream desktop PC's.

This paper describes an isolated power supply that provides system voltages to a PD operating from power supplied over Ethernet cables. The power supply consists of several sections: PoE controller, EMI filter, isolated power converter, and secondary converters. Although this power supply was designed specifically for use in a VoIP phone using TI's TNETV1050, it is generic in nature and could be used as-is or easily adapted for other PoE applications. The primary design objectives for the power supply were; low cost, small size, high efficiency and compliance with the IEEE802.3af standard. A complete schematic of this power supply can be seen in Figure 1. The complete list of materials for the circuit is in Table 1.

## 2 PoE Controller

The TPS2370 acts as an interface between the power sourcing equipment (PSE) and the powered device (PD), performing all detection, classification, inrush current limiting, and switch FET control necessary for compliance with the IEEE802.3af standard. The presence of a valid PD on the Ethernet line is detected when the PSE applies a voltage in the range of 1.8 V to 10 V to sense the 24.9-k $\Omega$  discovery resistor R2. The PD's classification is set when the PSE applies a voltage in the range of 15 V to 20 V to sense the classification resistor R5. The classification level of a PD identifies how much power the PD requires from the Ethernet line. An internal FET and control circuit limits the inrush and steady-state current drawn from the Ethernet line. R4 can be used to set a user defined in-rush current limit. C10 is used to eliminate oscillations at turn-on caused by line inductance. The IEEE802.3af standard limits the size of this input capacitor to 0.15  $\mu\text{F}$ . Transorb D7 protects against any transients that may couple into the Ethernet line. In this application, D1 to D4 isolate the Ethernet power from an external, regulated 48- $V_{\text{DC}}$  source. A diode bridge is also commonly used on the Ethernet line to protect against polarity reversal and provide automatic polarity correction. Detailed operation of the TPS2370 can be found in the datasheet, TI Literature No. SLUS537.

## 3 Input EMI Filter

Noise generated by the PD and the isolated power supply could interfere with the data being transmitted and operation of other PD devices connected to the same Ethernet line. IEEE802.3af specifies the maximum ripple allowed at the PI/PD interface to insure data integrity. This power supply operates at 100 kHz and the peak-to-peak voltage ripple limit at this frequency is 200 mV. It is important to keep in mind that there are harmonics to the fundamental 100-kHz frequency with different limits and the PD may also generate noise which adds to the filtering requirements. L1, C2, and C3 are a differential filter used to reduce the current pulses generated by the isolated supply. C2 and C3 are selected such that their combined RMS ripple current rating is equal to or greater than the rms input ripple current of the isolated supply. L1 is then selected to reduce the input ripple voltage below the IEEE802.3af requirements.

Noise common to both input power lines is also generated due to stray capacitance. L3 and C5 filter these common-mode currents. The IEEE802.3af limits are for common-mode and differential-mode ripple. Many PDs will also have to meet FCC/EU emission standards, so the design of the common mode filter should take this into account.[3]

## 4 Isolated Power Converter

A flyback converter with a self-driven synchronous rectifier on the 3.3-V output is used for this design.<sup>[4]</sup> The synchronous rectifier has a very small voltage drop compared to a schottky diode, increasing efficiency. Continuous current mode operation is required in order to have a drive waveform for the synchronous rectifier during the complete primary switch off time.

T1 is the flyback transformer (actually an inductor since it stores energy)<sup>[5]</sup>. MOSFET Q2 is switched on and off with a variable duty cycle and period of 100 kHz to allow T1 to store energy, which is delivered to the output capacitors and load during the Q2 off time. During the Q2 on time, capacitors C12 to C15 supply all of the load current. During the Q2 off time, the voltage between gate and source of Q1 is positive, turning it on. Current flows into capacitors C12 to C15, recharging them, and into the 3.3-V load. Inductor L4 and capacitor C16 filter the voltage ripple to an acceptable level. Filtering could be accomplished with only capacitors, but would require 2-to-3 times the number of capacitors currently used. Adding the LC filter is more cost effective and takes up less board area.

To regulate the 3.3-V output, the voltage is measured and compared to the reference in the TLV431A shunt regulator, U5. Opto-isolator U4 provides isolation in the feedback path. U3 is the UCC3809 PMW controller that controls the on time of Q2, thus regulating the 3.3-V output. Operation is as follows: If the 3.3-V output is too high, U5 draws more current. This same current is reflected to the output of the opto-isolator, U4, and develops a voltage across R12 and R20. A voltage is also generated across current sense resistor R10, which measures the current through Q2. The combination of these two voltages is fed into U3 to U1, the PWM comparator. When this voltage is below 1 V, switch Q2 is on. When this voltage reaches 1 V, Q2 turns off. The length of time Q2 is on controls the amount of energy stored in T1 and in turn regulates the amount of energy delivered to the secondary, regulating the 3.3-V output.

A second output voltage is generated by adding another winding to transformer T1 with the proper turns ratio. Schottky diode D5 is forward biased during the Q2 off time, allowing current to flow into capacitors C6, C7, C8 and the 5-V load. L2 and C9 filter the 5-V ripple to an acceptable level. Creating a second output in this manner results in a semi-regulated output with a tolerance of 8% to 10%, depending on input line and load. To obtain tighter regulation, the output is set a little higher than needed and a low dropout regulator is used to provide the tighter regulation. LDOs with a 1% to 2% tolerance are available.

## 5 Non-Isolated Power Converters

Two additional voltages are required for this PD. An adjustable 12 V to 24 V at 20 mA is required as a bias for an LCD display. A TPS61045 high-frequency boost converter in 3 mm x 3 mm QFN packaging, U6, is used to step up the 3.3-V output. The core voltage for the DSP requires 1.5 V at 250 mA. A TPS62210 synchronous buck converter in SOT-23-5, U7, is used to step down the 3.3-V output to 1.5 V at 87% efficiency. Both devices feature internal power switches and control loop compensation, reducing external component count, board space requirements and cost. Detailed operation of these converters can be found in their datasheets and applications notes.

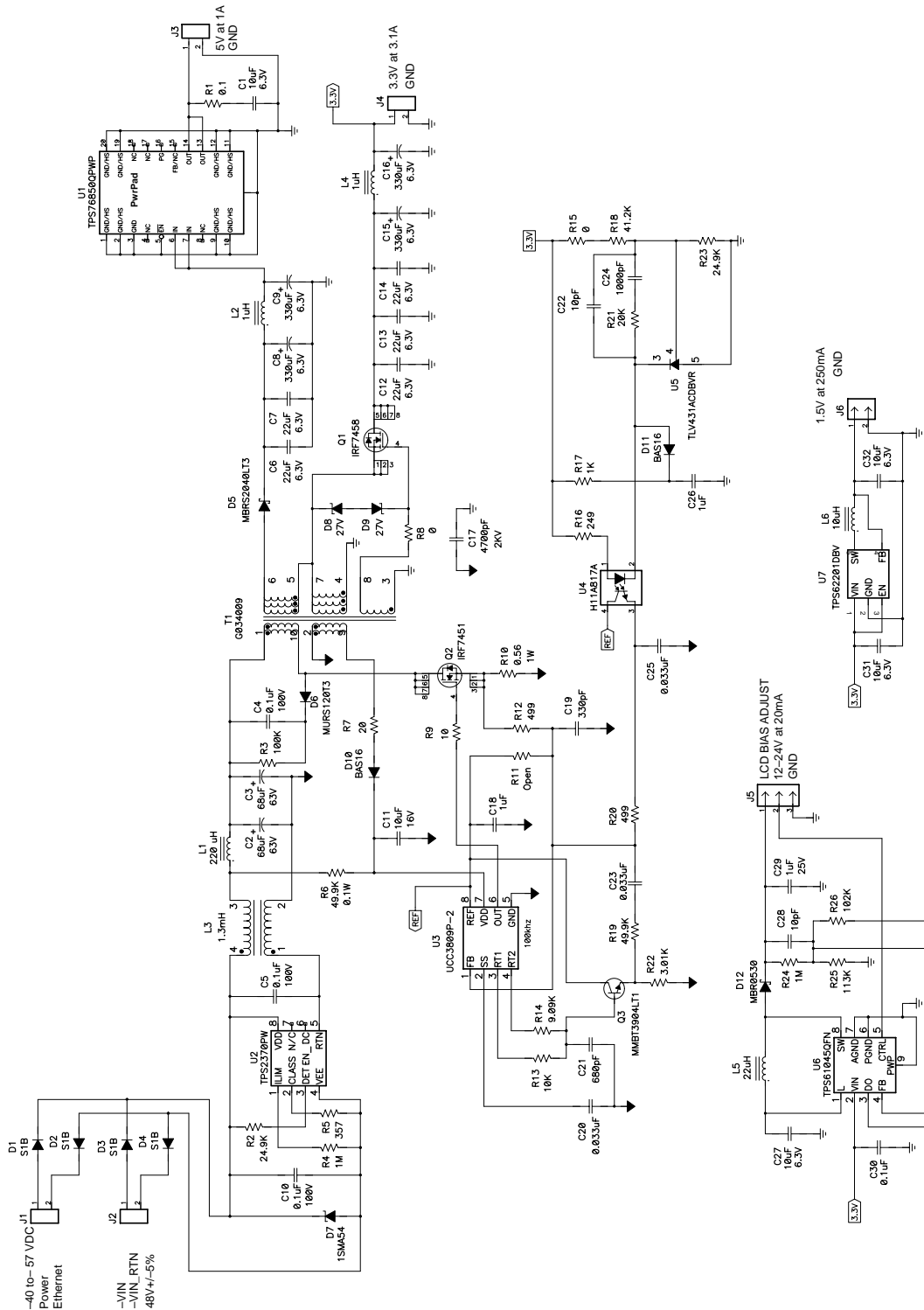


Figure 1. PoE Schematic

**Table 1. PoE List of Materials**

REFERENCE	QTY	DESCRIPTION	MANUFACTURER	PART NUMBER
C22, C28	2	Capacitor, ceramic, 10 pF, 50 V, C0G, 5%, 603	Std	Std
C19	1	Capacitor, ceramic, 330 pF, 50 V, C0G, 5%, 603	Std	Std
C21	1	Capacitor, ceramic, 680 pF, 50 V, C0G, 5%, 603	Std	Std
C24	1	Capacitor, ceramic, 1000 pF, 50 V, COG, 5%, 603	Std	Std
C20, C23, C25	3	Capacitor, ceramic, 0.033 $\mu$ F, 25 V, X7R, 10%, 603	Std	Std
C30	1	Capacitor, ceramic, 0.1 $\mu$ F, 25 V, X7R, 10%, 603	Std	Std
C18, C26	2	Capacitor, ceramic, 1 $\mu$ F, 16 V, X7R, 10%, 805	Std	Std
C1, C27, C31, C32	4	Capacitor, ceramic, 10 $\mu$ F, 6.3 V, X5R, 10%, 805	TDK	C1220X5R0J106K
C4, C5, C10	3	Capacitor, ceramic, 0.1 $\mu$ F, 100 V, X7R, 10%, 1206	Std	Std
C29	1	Capacitor, ceramic, 1 $\mu$ F, 25 V, X7R, 10%, 1206	TDK	C3216X7R1E105K
C11	1	Capacitor, ceramic, 10 $\mu$ F, 16 V, X5R, 20%, 1210	TDK	C3225X5R1C106M
C6, C7, C12, C13, C14	5	Capacitor, ceramic, 22 $\mu$ F, 6.3 V, X5R, 20%, 1210	TDK	C3225X5R0J226M
C17	1	Capacitor, ceramic, 4700 pF, 2 kV, X7R, 20%, 1812	AVX	1812CG472MAT
C8, C9, C15, C16	4	Capacitor, aluminum, SM, 330 $\mu$ F, 6.3 V, 8x6.2mm	Panasonic	EEVFK0J331P
C2, C3	2	Capacitor, aluminum, SM, 68 $\mu$ F, 63V, 10x10mm	Panasonic	EEVFK1J680P
D10, D11	2	Diode, switching, 200 mA, 75 V, 225 mW, SOT-23	On Semi	BAS16LT1
D8, D9	2	Diode, zener, 27 V, 225 mW, SOT-23	On Semi	BZX84C27LT1
D12	1	Diode, schottky, 0.5 A, 30 V, SOD-123	On Semi	MBR0530T1
D5	1	Diode, schottky, 2 A, 40 V, SMB	On Semi	MBRS2040LT3
D6	1	Diode, ultra fast rectifier, 1 A, 200 V, SMB	On Semi	MURS120T3
D1, D2, D3, D4	4	Diode, rectifier, 1 A, 100 V, SMA	Diodes, Inc.	S1B
D7	1	Diode, TVS, 54 V, 400 W, SMA	On Semi	1SMA54AT3
L2	1	Inductor, SMT, 1 $\mu$ H, 2.9A, 50 m $\Omega$ , 4.45x6.6mm	Coilcraft	DO1608C-102
L6	1	Inductor, SMT, 10 $\mu$ H, 1.1A, 160 m $\Omega$ , 4.45x6.6mm	Coilcraft	DO1608C-103
L5	1	Inductor, SMT, 22 $\mu$ H, 0.7A, 370 m $\Omega$ , 4.45x6.6mm	Coilcraft	DO1608C-223
L4	1	Inductor, SMT, 1 $\mu$ H, 6.8A, 9 m $\Omega$ , 9.4x12.95mm	Coilcraft	DO3316P-102
L1	1	Inductor, SMT, 220 $\mu$ H, 500 mA, 390 m $\Omega$ , 0.51x0.37	Coilcraft	DT3316P-224
L3	1	Inductor, common mode, 1.3 mH, 0.7 A, 500 m $\Omega$ , 0.690 * 0.610"	GCI [6]	UU9.8H-132
T1	1	Transformer, flyback, 2 primary, 3 secondary, custom, 1.18x0.886"	GCI [6]	G034009
R15	1	Resistor, chip, 0 $\Omega$ , 603	Std	Std
R1	1	Resistor, chip, 0.10 $\Omega$ , 1/16 W, 1%, 603	Panasonic	Std
R16	1	Resistor, chip, 249 $\Omega$ , 1/16 W, 1%, 603	Std	Std
R5	1	Resistor, chip, 357 $\Omega$ , 1/16 W, 1%, 603	Std	Std
R12, R20	2	Resistor, chip, 499 $\Omega$ , 1/16 W, 1%, 603	Std	Std
R17	1	Resistor, chip, 1.00 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R22	1	Resistor, chip, 3.01 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R14	1	Resistor, chip, 9.09 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R13	1	Resistor, chip, 10.0 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R21	1	Resistor, chip, 20.0 k $\Omega$ , 1/16 W, 1%, 603	Std	Std

REFERENCE	QTY	DESCRIPTION	MANUFACTURER	PART NUMBER
R2, R23	2	Resistor, chip, 24.9 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R18	1	Resistor, chip, 41.2 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R19	1	Resistor, chip, 49.9 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R26	1	Resistor, chip, 102 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R25	1	Resistor, chip, 113 k $\Omega$ , 1/16 W, 1%, 603	Std	Std
R4, R24	2	Resistor, chip, 1.00 M $\Omega$ , 1/16 W, 1%, 603	Std	Std
R11	1	Resistor, chip, Open, 1/16 W, 1%, 603	Std	Std
R8	1	Resistor, chip, 0 $\Omega$ , 805	Std	Std
R9	1	Resistor, chip, 10 $\Omega$ , 1/10 W, 5%, 805	Std	Std
R7	1	Resistor, chip, 20 $\Omega$ , 1/10 W, 5%, 805	Std	Std
R6	1	Resistor, chip, 49.9 k $\Omega$ , 1/10 W, 1%, 805	Std	Std
R3	1	Resistor, chip, 100 k $\Omega$ , 1/10 W, 1%, 805	Std	Std
R10	1	Resistor, chip, 0.56 $\Omega$ , 1 W, 1%, 2512	Std	Std
J1, J2, J3, J4	4	Terminal block, 2 pin, 6 A, 3.5 mm, 0.27 x 0.25"	OST	ED1514
J6	1	Header, 2 pin, 100-mil spacing, (36-pin strip), 0.100 x 2	Sullins	PTC36SAAN
J5	1	Header, 3 pin, 100-mil spacing, (36-pin strip), 0.100 x 3	Sullins	PTC36SAAN
U4	1	IC, optocoupler, 5300 V, 80% to 160% CTR, 0.380 x 0.180	Fairchild	H11A817A
Q3	1	Bipolar, NPN, 40 V, 200 mA, 225 mW, SOT-23	On Semi	MMBT3904LT1
Q2	1	MOSFET, N-channel, 150 V, 3.6 A, 90 m $\Omega$ , SO-8	IR	IRF7451
Q1	1	MOSFET, N-channel, 30 V, 14 A, 8 m $\Omega$ , SO-8	IR	IRF7458
U3	1	IC, economy primary-side controller, MSOP-8	Texas Instruments	UCC3809P-2
U5	1	IC, shunt regulator, 1.24 V Ref, 6V, 10 mA, 1%, SOT23-5	Texas Instruments	TLV431ACDBVR
U1	1	IC, 1A LDO regulator, 5 V, TSSOP-20	Texas Instruments	TPS76850QPWP
U2	1	IC, hot-swap switch for PoE power devices, TSSOP8-PW	Texas Instruments	TPS2370PW
U7	1	IC, step-down converter, 1.5 V, 300 mA, SOT23-5	Texas Instruments	TPS62201DBV
U6	1	IC, adjustable LCD boost converter, QFN-8	Texas Instruments	TPS61045QFN

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