TI Designs
2-Wire Galvanically Isolated IC Temperature Sensor With Pulse Count Interface

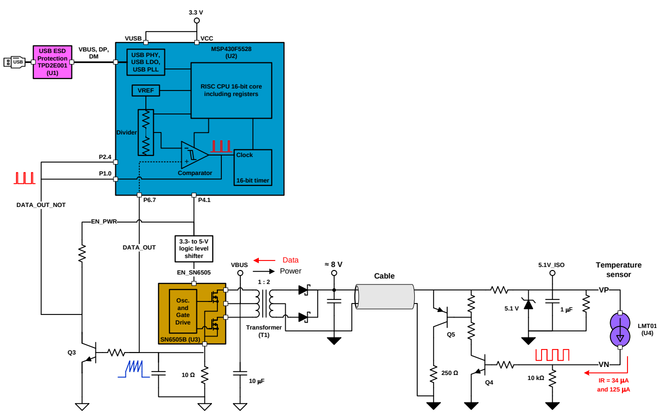
TI Designs

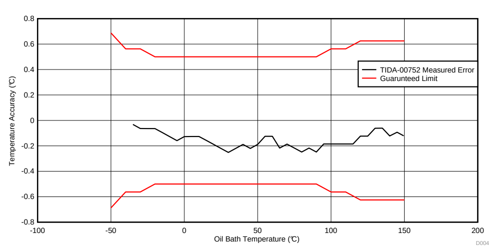
This TI Design is an accurate and robust solution for remote temperature sensing that works in an indoor or outdoor building environment.

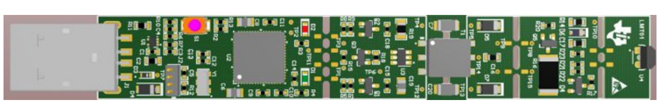
Design Resources

TIDA-00752	Design Folder
LMT01	Product Folder
SN6505	Product Folder
MSP430F5528	Product Folder
TPD2E001	Product Folder

TI E2E™ Community — ASK Our E2E Experts







Design Features

- Allows Single Low-Profile Transformer for Power and Data Isolation While Eliminating the Need for Optocoupler or Digital Isolator on Data Line
- Power and Data Coexist on 2–Wire Interface for Remote Temperature Sensing Across Isolation
- No Need of System Level Calibration Unlike Thermistors
- Replacement for RTDs and NTC or PTC Thermistors
- Eliminates High-Precision Active or Passive Components
- Functional Isolation of 400 V_{RMS} and Dielectric up to 2500-V AC for 60 seconds
- Pre-Compliance Testing: Meets IEC61000-4-4 EFT (Level 4): ±2 kV – Class-A
- Accuracy Over Temperature:
  – Measured Error Using LUT: < 0.25ºC (-35ºC to 150ºC)
  – Measured Error Using First Order Transfer Function: < 0.25ºC (15ºC to 100ºC)
  – Guaranteed Limits From LMT01 Datasheet Using LUT: < 0.5 max. (–20ºC to 90ºC), 0.62 max. (90ºC to 150ºC), < 0.7 max. (–50ºC to –20ºC)

Featured Applications

- Building Automation: HVAC and Elevators
  – Duct Temperature Measurement
  – Clip-on Temperature Sensor for Refrigerant Copper Pipes
  – Ring Lug Surface Temperature Sensor
  – Temperature Sensor for Motor Protection
  – Compressor Discharge Temperature Monitor
- Digital Temperature Sensor Probe Assemblies
- Factory Automation and Process Control

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1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATION	DETAILS
Sensor type	High accuracy, 2-pin digital output temperature sensor IC with pulse count interface	Section 3.1
Temperature sensor package	2-pin TO-92/LGP (3.1 × 4 × 1.5 mm), half the size of a traditional TO-92	Section 3.1
Sensor temperature range	–50ºC to 150ºC	Section 3.1
Resolution	0.0625ºC	Section 3.1 and Section 4.3.2
System accuracy or maximum measured error	Using LUT: • For –35ºC to 150ºC range: < 0.25ºC max.	Section 6.4
	Using first order transfer function: • For –50ºC to 150ºC range: < 2ºC max. • For 15ºC to 100ºC range: < 0.25ºC max. • For 30ºC to 90ºC range: < 0.1ºC max. (Better results than LUT for short temperature range)	Section 6.4
	Guaranteed limits from LMT01 datasheet using LUT: • For –20ºC to 90ºC range: < 0.5 max. • For 90ºC to 150ºC range: < 0.62 max. • For –50ºC to –20ºC range: < 0.7 max.	Section 3.1
Calibration	No calibration required during production or in the field	Section 4.1.1
Sensor linearization	First order polynomial equation or compact look-up table	Section 4.3.2
Operating voltage	4.25 to 5.35 V (USB VBUS)	Section 4.1.3
Power consumption	≈ 16 mA	Section 4.3
Continuous conversion time + Data transmission time	54 ms + 50 ms = 104 ms (max), which means 9 samples per seconds in continuous conversion mode	Section 4.3
Isolation type	Galvanic isolation using single low cost low profile transformer for both power and data transfer	Section 4.3.1
Dielectric	2500-V AC for 1 minute	Section 4.3.1
Functional isolation or continuous working voltage	400-V_{RMS} or 560-V peak	Section 4.3.1
IEC EFT testing	IEC61000-4-4 (Level-4): ±2 kV – Class A using capacitive coupler	Section 6.5
Working environment	Building indoor or outdoor environment	Section 4.4
Connectivity interface	USB2.0	Section 4.1.2
Debugging interface	4-pin Spy-Bi-Wire™ (SBW) interface	—
PCB breakout slots	Three perforated slots allow user to break apart the PCB and insert long wires for remote temperature measurement.	Section 5.1
Form factor	USB stick form factor	Section 5.1
Remote temperature sensing	Tested with 30-m long shielded twisted pair cable	Section 5.2
Sensor wiring diagnostic	Sensor wire open or short circuit fault detection	Section 4.5

2 System Description

Any temperature sensor connected to wires in a hostile environment can have its performance adversely affected by intense electromagnetic sources such as radio transmitters, induction heating systems, high-speed power switching elements, large solenoids, relays, motors with arching brushes, high AC voltage and current conductors, poorly grounded environments, interference from electrical transients, welders, lightning strikes, and so on. In such situations, lacking isolation impairs safety and induces electromagnetic interference (EMI). Therefore, it becomes necessary to provide galvanic isolation between the hazardous high voltage side and low voltage controller side. Electrically isolating the sensor provides safety and seamless voltage level shifting and eliminates ground noise, which ultimately enhances performance and reliability while making the system design more complicated because power and data need to be transferred across an isolation barrier. One would use one transformer for power isolation and another transformer, optocoupler, or digital isolator for isolating the data, which increases complexity, cost, and footprint of the overall temperature measuring solution.

The 2-Wire Galvanically Isolated IC Temperature Sensor with Pulse Count Interface reference design provides system designers the recommendations on how to design a new cost-effective, easy to use, small form factor, accurate, repeatable, and electrically isolated temperature measurement system based on a new digital output IC temperature sensor. The new tiny 2-pin digital output IC temperature sensor with a single wire pulse count interface enhances reliability and greatly simplifies the design of galvanic isolation architecture for sending both power and unidirectional data through a single low-cost, low-profile transformer. The 2500-V AC breakdown barrier between the temperature sensor and power/data ports permit operation at high common-mode voltage enhancing safety and data integrity. For example, isolation protects sensitive circuit components and human interface on the system side from potentially dangerous voltage levels present on the field side. Isolation also eliminates ground loops that affect the measurement accuracy. By simply following the recommendations provided, the user can realize remote temperature sensing over long cables with lengths while achieving the performance as stated in the datasheet specification. With a less than ±0.25°C maximum measured error and a ±0.7°C guaranteed error over temperature range of -50°C to 150°C, functional isolation of 400 V_{RMS}, and IEC61000-4-4 pre-compliance testing, this design significantly reduces the design time of a high-accuracy temperature measurement system.

This reference design subsystem is highly differentiated over existing solutions by offering the following benefits:

- Innovative approach allows single low-profile transformer for power and data isolation while eliminating the need of optocoupler or digital isolator on data line
- Eliminates high precision active or passive components like high PSRR LDO, ADC, instrumentation amplifier, op amps, voltage reference, analog multiplexer, filters or better tolerance resistors, and capacitors
- Power and data coexist on 2-wire interface for remote temperature sensing across isolation
- Functional isolation of 400 V_{RMS} and dielectric up to 2500-V AC for 60 seconds
- No special power supply requirements; a simple open loop DC-DC power supply with high switching frequency of 420 kHz that eliminates traditional bulky transformer
- Eliminating complex calibration schemes, which saves cost during manufacturing and in after sales servicing
- Replacement for RTDs and NTC/PTC thermistors
- Pre-compliance testing: Meets IEC61000-4-4 EFT (Level 4): ±2 kV – Class A with shielded twisted pair cable
- Sensor wire open or short circuit fault detection without any additional hardware
- No measurement error due to jitter, propagation delay, and rise or fall time of isolated signal output
- Extremely easy for system designers to get started with this approach and access market faster than ever
- With only one error source (the sensor itself), computation of error budget is pretty straightforward and honest
- Gets performance as stated in the datasheet specification

At a high level, the 2-Wire Galvanically Isolated IC Temperature Sensor with Pulse Count Interface Reference Design system consists of a high accuracy digital output IC temperature sensor, push-pull transformer driver, system MCU, ESD protection device, and power management.

The overall system-level requirements for this reference design include:

- *Overall system accuracy*: The system must be designed to meet the overall system error specification. The maximum measured error must be less than ±0.5°C for a temperature range of 0°C to 100°C and less than 0.7°C for temperatures below 0°C and above 100°C.
- *Remote sensor operation*: In remote sensing applications, the costs are kept to a minimum by reducing the amount of running copper over long distances. Therefore, the system must send temperature measurements across isolation over long distances through 2-wire link without any loss of accuracy due to system wiring.
- *Galvanic isolation*: The isolation barrier must be designed to have a minimum dielectric withstand rating of 2000 V_{RMS} for 60 seconds and a continuous working voltage of 250 V_{PEAK}.
- *Calibration and compensation*: The system must require zero calibration during manufacturing and in the field for quick and easy maintenance and minimizing amount of system downtime.
- *Noise immunity*: The system must be designed to meet IEC61000-4-4 EFT to provide robust temperature monitoring with improved accuracy and noise immunity at reduced overall system cost.
- *Less system complexity*: The system must be simple and easy to use by minimizing number of components and software protocol overheads.
- *Solution size*: Entire solution needs to be in a small form factor design that can be easily installed.

This design guide addresses component selection, design theory, and test results of the TI Design system. The scope of this design guide gives system designers a head-start in integrating TI's industrial temperature sensor, push-pull transformer driver, system MCU, ESD protection device, and power management technologies into their end-equipment systems. This reference design provides a complete set of downloadable documents such as a comprehensive design guide, schematic, Altium PCB layout files, Gerber files, bill of materials (BOM), test results, firmware, and GUI that helps system designers in the design and development of their end-equipment systems.

The following subsections describe the various blocks within the TI Design system and what characteristics are most critical to best implement the corresponding function.

3 Block Diagram

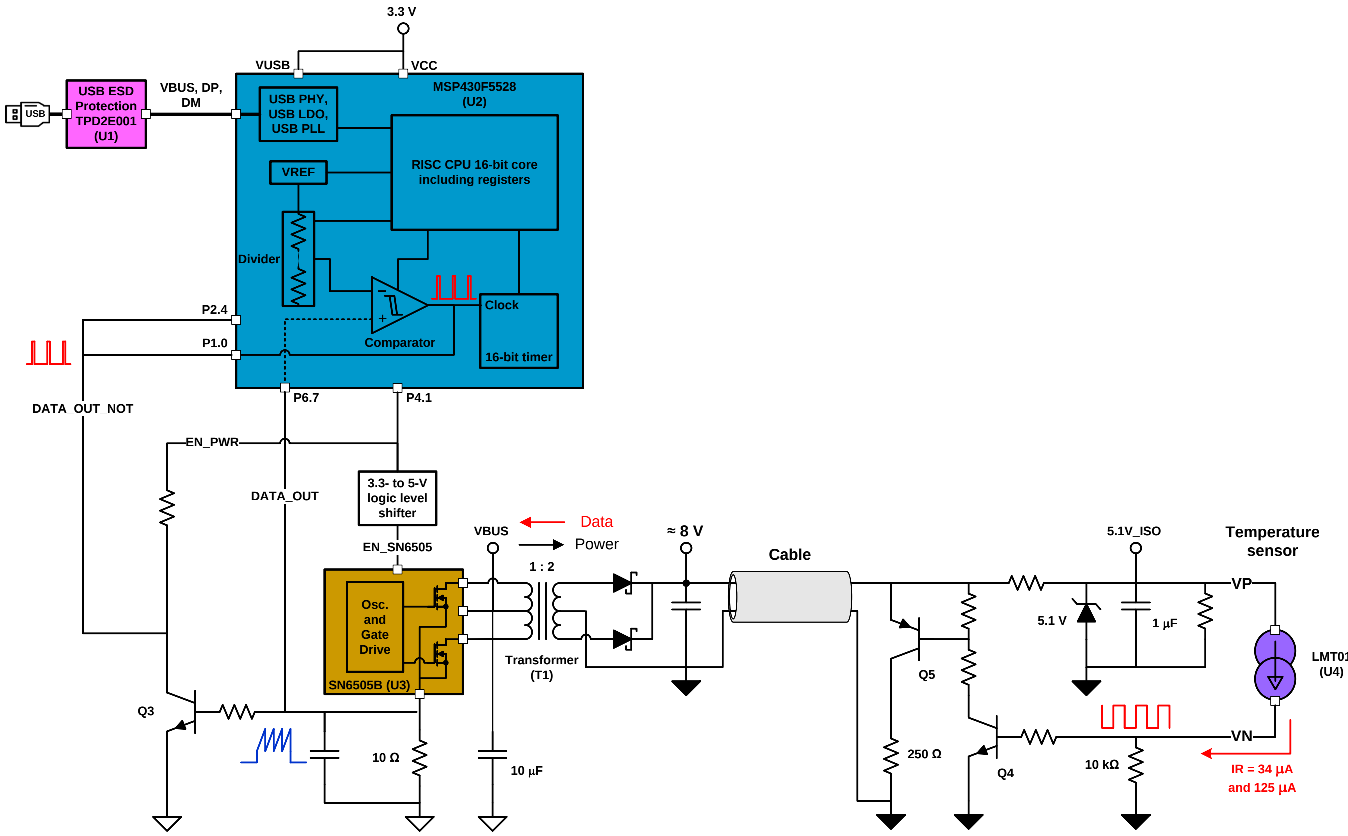

Figure 1. Conceptual Schematic Diagram of 2-Wire Galvanically Isolated IC Temperature Sensor With Pulse Count Interface (TIDA-00752)

3.1 Highlighted Products

The 2-Wire Isolated Temperature Sensor Reference Design features the following devices:

- LMT01: 0.5°C Accurate 2-Pin Digital Output Temperature Sensor with Pulse Count Interface
- SN6505: Low-Noise 1-A Transformer Driver for Isolated Power Supplies
- MSP430F5528: 16-Bit Ultra-Low-Power Microcontroller, 128KB Flash, 8KB RAM, USB, 12-Bit ADC, 2 USCIs and 32-Bit HW MPY
- TPD2E001: Low-Capacitance 2-Channel ±15-kV ESD-Protection Array for High-Speed Data Interfaces

For more information on each of these devices, see their respective product folders at www.ti.com.

3.1.1 LMT01

Features

- High accuracy over –50°C to 150°C wide temperature range:
  - –20°C to 90°C: ±0.5°C (max)
  - 90°C to 150°C: ±0.62°C (max)
  - –50°C to –20°C: ±0.7°C (max)
- Precision digital temperature measurement simplified in a 2-pin package
- Single-wire pulse count digital output easily read with processor timer input
- Number of output pulses is proportional to temperature with 0.0625°C resolution
- Communication frequency: 88 kHz
- Continuous conversion plus data-transmission period: 100 ms
- Conversion current: 34 µA
- Floating 2 to 5.5-V (VP–VN) supply operation with integrated EMI immunity
- 2-pin package offering TO-92/LPG (3.1 × 4 × 1.5 mm), half the size of a traditional TO-92

Applications

- Digital output wired probes
- White goods
- HVAC
- Power supplies
- Industrial Internet of Things (IoT)
- Automotive
- Battery management

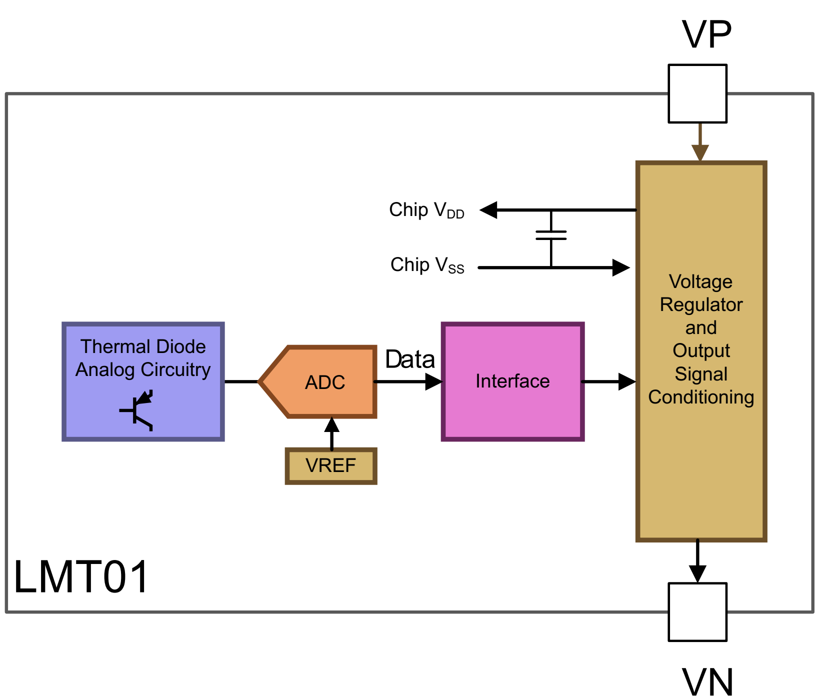

Figure 2. LMT01 Functional Block Diagram

The LMT01 is a high-accuracy, 2-pin temperature sensor with an easy-to-use pulse count interface, which makes it an ideal digital replacement for PTC or NTC thermistors both on and off board in automotive, industrial, and consumer markets. The LMT01 digital pulse count output and high accuracy over a wide temperature range allow pairing with any MCU without concern for integrated ADC quality or availability while minimizing software overhead. TI's LMT01 achieves flat ±0.5°C accuracy with very fine resolution (0.0625°C) over a wide temperature range of –20°C to 90°C without system calibration or hardware or software compensation.

Unlike other digital IC temperature sensors, the LMT01's single wire interface is designed to directly interface with a GPIO or comparator input, thereby simplifying hardware implementation. Similarly, the LMT01's integrated EMI suppression and simple 2-pin architecture makes it ideal for onboard and off-board temperature sensing. The LMT01 offers all the simplicity of analog NTC or PTC thermistors with the added benefits of a digital interface, wide specified performance, EMI immunity, and minimum processor resources.

3.1.2 SN6505

Features

- Push-pull driver for transformers
- Wide input voltage range: 2.25 to 5.5 V
- High output drive: 1 A at 5-V supply
- Low R_{ON}: 0.25 Ω max at 4.5-V supply
- Ultra-low EMI
- Spread spectrum clocking
- Precision internal oscillator options: 160 kHz (SN6505A) and 420 kHz (SN6505B)
- Synchronization of multiple devices with external clock input
- Slew-rate control
- 1.7-A current limit
- Low shutdown current: < 1 µA
- Thermal shutdown
- Wide temperature range: –55°C to 125°C
- Small 6-pin SOT23/DBV package
- Soft start to reduce inrush current

Applications

- Isolated power supply for CAN, RS-485, RS-422, RS-232, SPI, I^2C, and low-power LAN
- Low-noise isolated USB supplies
- Process control
- Telecom supplies
- Radio supplies
- Medical instruments
- Distributed supplies
- Precision instruments
- Low-noise filament supplies

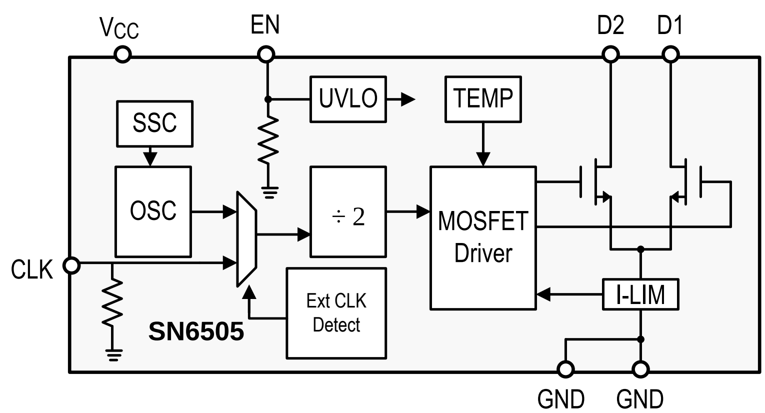

Figure 3. SN6505 Functional Block Diagram

The SN6505 is a transformer driver designed for low-cost, small form-factor, isolated DC-DC converters utilizing the push-pull topology. The device includes an oscillator that feeds a gate-drive circuit. The gate-drive, comprising a frequency divider and a break-before-make (BBM) logic, provides two complementary output signals which alternately turn the two output transistors on and off.

The output frequency of the oscillator is divided down by two . A subsequent break-before-make logic inserts a dead-time between the high-pulses of the two signals. Before either one of the gates can assume logic high, the BBM logic ensures a short time period during which both signals are low and both transistors are high-impedance. This short period, is required to avoid shorting out both ends of the primary. The resulting output signals, present the gate-drive signals for the output transistors.

3.1.3 MSP430F5528

Features

- Low supply voltage range: 3.6 V down to 1.8 V
- Ultra-low power consumption
  - Active mode (AM):
    - All system clocks active:
      - 290 µA/MHz at 8 MHz, 3.0 V, flash program execution (typical)
      - 150 µA/MHz at 8 MHz, 3.0 V, RAM program execution (typical)
    - Standby mode (LPM3):
      - Real-time clock (RTC) with crystal, watchdog, and supply supervisor operational, full RAM retention, fast wake up:
        - 1.9 µA at 2.2 V, 2.1 µA at 3.0 V (typical)
      - Low-power oscillator (VLO), general-purpose counter, watchdog, and supply supervisor operational, full RAM retention, fast wake up:
        - 1.4 µA at 3.0 V (typical)
    - Off mode (LPM4):
      - Full RAM retention, supply supervisor operational, fast wake up:
        - 1.1 µA at 3.0 V (typical)
  - Shutdown mode (LPM4.5):
    - 0.18 µA at 3.0 V (typical)
- Wake up from standby mode in 3.5 µs (typical)
- 16-bit RISC architecture, extended memory, up to 25-MHz system clock
- Flexible power management system:
  - Fully integrated LDO with programmable regulated core supply voltage
  - Supply voltage supervision, monitoring, and brownout
- 16-bit timer TA0, Timer_A with five capture/compare registers
- 16-bit timer TA1, Timer_A with three capture/compare registers
- 16-bit timer TA2, Timer_A with three capture/compare registers
- 16-bit timer TB0, Timer_B with seven capture/compare shadow registers
- Two universal serial communication interfaces:
  - USCI_A0 and USCI_A1 each support:
    - Enhanced UART supports automatic baud rate detection
    - IrDA encoder and decoder
    - Synchronous SPI
  - USCI_B0 and USCI_B1 each support:
    - I^2C
    - Synchronous SPI
- Full-speed universal serial bus (USB)
  - Integrated USB-PHY
  - Integrated 3.3-V and 1.8-V USB power system
  - Integrated USB-PLL
  - Eight input and eight output endpoints
- 12-bit analog-to-digital converter (ADC) (MSP430F552x only) with internal reference, sample-and-hold, and auto-scan feature
- Comparator
- Hardware multiplier supports 32-bit operations
- Serial onboard programming, no external programming voltage needed
- Three-channel internal DMA
- Basic timer with RTC feature
- For complete module descriptions, see the *MSP430x5xx and MSP430x6xx Family User's Guide* (SLAU208)

Applications

- Analog and digital sensor systems
- Connection to USB hosts
- Data loggers

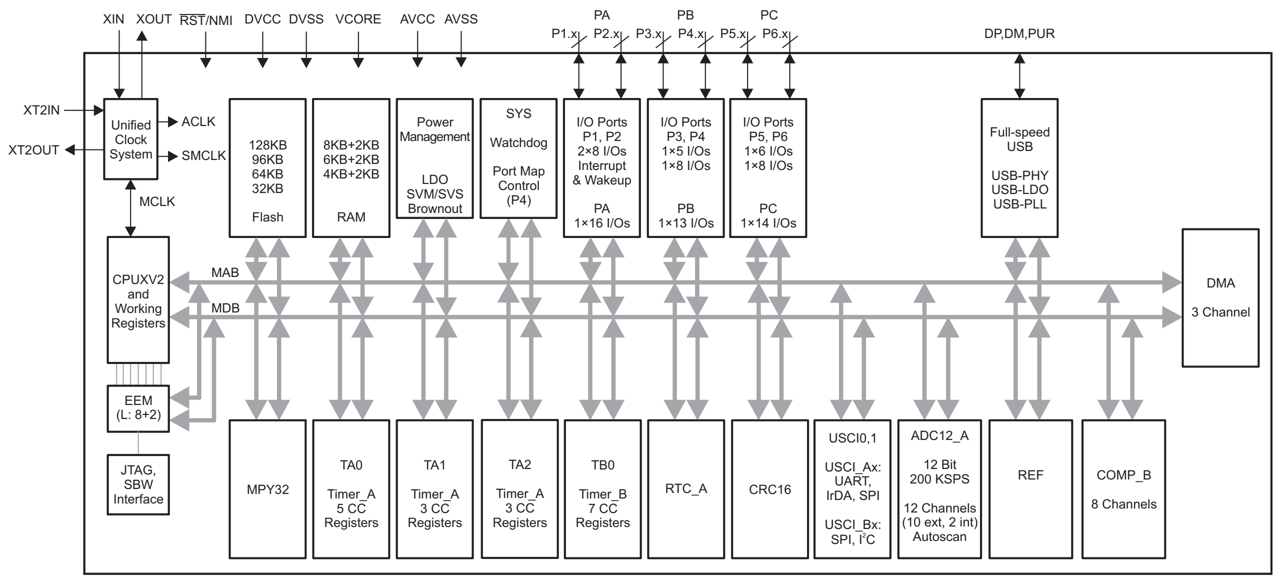

Figure 4. MSP430F5528 Functional Block Diagram

Figure 4 shows the functional block diagram for the MSP430F5528 in the RGC and ZQE packages and in the YFF package.

3.1.4 TPD2E001

Features

- IEC 61000-4-2 ESD protection (level 4):
  - ±8-kV contact discharge
  - ±15-kV air-gap discharge
- IO capacitance: 1.5 pF (typical)
- Low leakage current: 1 nA (max)
- Low supply current: 1 nA
- 0.9- to 5.5-V supply voltage range
- Space-saving DRL, DRY, and QFN package options
- Alternate 3-, 4-, and 6-channel options available: TPD3E001, TPD4E001, TPD6E001

Applications

- USB 2.0
- Ethernet
- FireWire™
- LVDS
- SVGA video connections
- Glucose meters
- Medical imaging

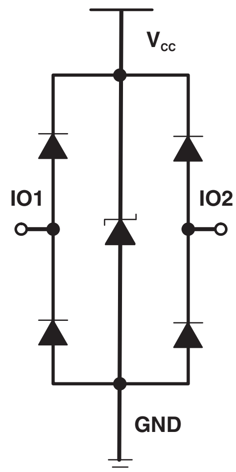

Figure 5. TPD2E001 Functional Block Diagram

The TPD2E001 is a uni-directional ESD protection device with low capacitance. The device is constructed with a central ESD clamp that features two hiding diodes per line to reduce the capacitive loading. This central ESD clamp is also connected to V_{CC} to provide protection for the V_{CC} line. Each IO line is rated to dissipate ESD strikes above the maximum level specified in the IEC 61000-4-2 level 4 international standard. The TPD2E001's low loading capacitance makes it ideal for protection high-speed signal terminals.

4 System Design Theory and Considerations

4.1 Component Selection

Before starting the circuit design and layout of the actual system, this reference design carefully examine all the captured system level requirements and features. Then, use a top-down approach to translate these system level requirements into subsystem or component level requirements that helps in selecting the right set of devices. Some of the subsystem or component level requirements are as follows.

4.1.1 Selecting a Temperature Sensor

Selecting a temperature sensor is a critical part in the design of any temperature measurement system because the reliability, stability, and accuracy of the entire system cannot be better than that of the sensing element. Selecting a temperature sensor is also very important because it decides the overall system architecture and greatly influences the selection of other supporting devices. The right temperature sensor depends upon various factors such as operating temperature range, accuracy, linearity, sensitivity, interchangeability, repeatability, stability and drift, corrosion and contamination effects, lead-wire resistance, cost, power consumption, size, mounting, design cycle time, and ease of designing the necessary support circuit. From a system level standpoint, the temperature sensor must satisfy the following requirements:

- The temperature sensor must have a minimum operating temperature range of –40°C to 125°C.
- The temperature sensor must simplify the design of galvanic isolation architecture.
- The temperature sensor must be available in a smaller package, which makes it easy to mount the sensor inside sealed metallic housing or lug to produce standard or custom probe assemblies.
- The temperature sensor must not have more than two pins that reduce the amount of copper running over long distances in wire-limited or remote-sensing applications.
- The temperature sensor’s lead-wire resistance must not introduce significant errors.
- The temperature sensor must have very little self-heating effect.
- The temperature sensor must have superior noise immunity.

A good place to start is to look at some of the available temperature sensor options and weigh the pros and cons of each. Figure 6 highlights some of the popular options available today.

Criteria	Thermocouple	RTD	Thermistor	Semiconductor
Temperature range (typical values)	Very wide –200°C to +2000°C	Wide –200°C to +650°C	Narrow –50°C to +300°C	Narrow –50°C to +200°C
Accuracy	Medium	High	Medium	High
Repeatability	Fair	Excellent	Fair to good	Good to excellent
Long-term stability	Poor to fair	Good	Poor	Good
Sensitivity (out)	Low	Medium	Very high	High
Linearity	Fair	Good	Poor	Good
Response	Medium to fast	Medium	Medium to fast	Medium to fast
Size/Packaging	Small to large	Medium to small	Small to medium	Small to medium
Interchangeability	Good	Excellent	Poor to fair	Good
Point (end) sensitivity	Excellent	Fair	Good	Good
Lead effect	High	Medium	Low	Low
Self heating	No	Very low to low	High	Very low to low
Overall advantages	Self powered, simple, inexpensive, rugged, variety of physical forms, wide range of temperature	Most stable, most accurate, more linear than thermocouple	High output, fast, two-wire ohms measurement	Most linear, highest output, inexpensive
Overall disadvantages	Non-linear, low voltage, reference required, least stable, least sensitive	Expensive, slow, current source required, small resistance change, four-wire measurement	Non-linear, limited temperature range, fragile, current source required	T < 250°C, power supply required

Figure 6. Common Temperature Sensors

Each sensor type has its own strengths (for example, accuracy, stability, cost, temperature range, and so on) that make it better suited to certain types of applications. For example, high temperature applications such as flame detection in boiler systems approach temperatures of several hundred to up to a thousand degrees require the use of RTDs or thermocouples. The majority of temperature-sensing applications, particularly in building automation and HVAC systems, measuring refrigerant, water, and air temperatures are limited to a range from 0°C to 100°C. This temperature range is commonly monitored by temperature probes utilizing either RTDs or thermistors. RTDs are perceived as the more accurate and stable over wide temperature range, but also more costly, whereas thermistors are most sensitive and low-cost alternative but with high nonlinearity and larger resistance drift over time.

From Figure 6, it is quite evident that thermocouple, RTD, thermistor or IC temperature sensor-based solutions have a number of design drawbacks such as the accumulated error of all the components, power consumption, linearity, quantization noise, calibration, operating temperature range, complexity, board area, and production cost. Each temperature sensor has its own advantages and disadvantages. Therefore, this reference design uses a new tiny LMT01 (see Figure 7) to address most of these design drawbacks. Standalone IC temperature sensors have rarely been considered for implementation into sensor probes or assemblies due to their larger geometries. However, designers exploit the process technology of these IC temperature sensors to everyone's advantage. The LMT01 is a complete temperature data-acquisition system on a monolithic silicon chip. A silicon-based sensor, internal voltage reference, and delta-sigma ADC all fit in a 2-pin (power and ground) TO-92/LGP package (half the size of traditional TO-92) while delivering unmatched value-for-performance such as high accuracy over time and temperature, very low power consumption, and simple design-in capability. Integrating the whole temperature-to-digital signal chain on a single chip, therefore, saves space, design time, and money. Now, system designers need not worry about power supply noise, complex linearization algorithms, cold-junction compensation, comparators, additional ADCs, voltage references, and so on. Unlike analog temperature sensors, the pulse count interface of the LMT01 offers superior noise immunity especially in remote sensing applications.

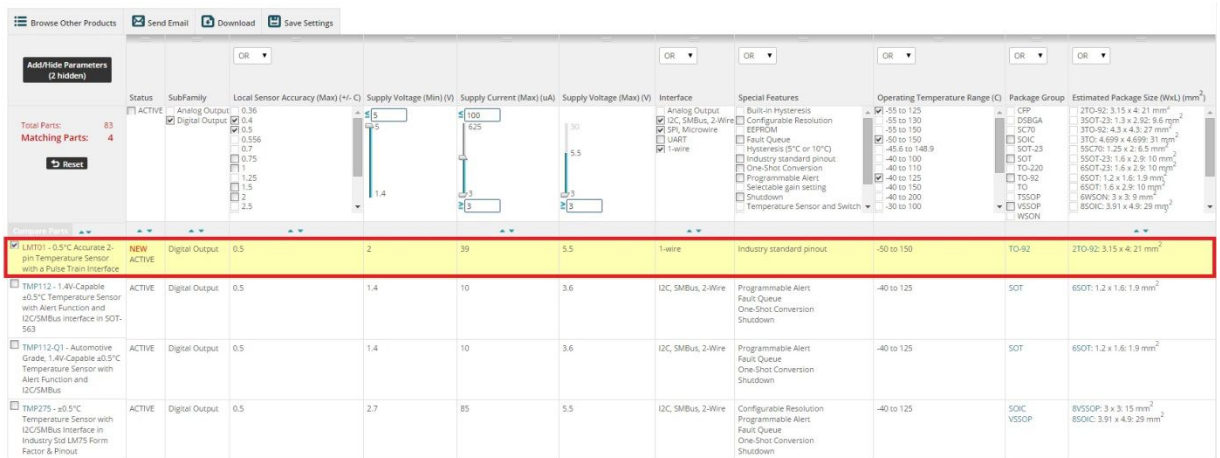

Figure 7. Parametric Table for Selecting Temperature Sensor

4.1.2 Selecting an Ultra-Low Power Microcontroller (MCU)

The 2-Wire Galvanically Isolated IC Temperature Sensor with Pulse Count Interface reference design has relatively few requirements for the MCU. This TI Design reproduces the LMT01 pulses on the MCU side across isolation barrier that needs to be counted by the MCU to know the temperature. There are various methods for pulse counting utilizing common resources such as GPIOs with interrupt capability, timers, and comparators, which are available on virtually any low cost MCU. In addition, this TI Design needs USB connectivity with a PC or laptop for easy transfer of data to GUI that aids in testing and demonstration.

Because this TI Design is meant to demonstrate TI technology, the USB-equipped MSP430F5528 device was selected as the system MCU. This device fulfills all the requirements of this TI Design subsystem, and features ultra-low power performance.

4.1.3 Selecting a Power Configuration

This TI Design has few power supply requirements. The design's hardware is configured to be powered from a standard USB host that provides nominal voltage of 5 V over the USB cable, called VBUS. The USB VBUS may vary from 4.25 to 5.35 V. Because this design will be permanently tethered to the USB host, this eliminates the need for a separate local power supply. This design requires a regulated non-isolated 3.3-V voltage rail for all components on the low-voltage side and an unregulated isolated DC/DC converter generating 8 V on the field side.

4.1.3.1 Regulated Non-Isolated 3.3-V Voltage Rail

As USB hosts source 5 V over the bus, an LDO is required to drop the voltage to the 3.3-V nominal of ICs on low voltage side. The USB-equipped MSP430 devices simplify power design and conserve board space by integrating an efficient LDO as well as associated pull-up functionality. This eliminates the need for a system LDO. In addition to allowing the MSP430 to operate directly from 5 V, integrating the LDO and pullup resistors reduces component count and saves cost relative to discrete implementations. The 3.3-V voltage rail can be used to source:

- On-chip USB module
- MSP430 DVCC power rail (most MSP430 devices use a 1.8- to 3.6-V DVCC rail)
- Rest of the board

The connection between the LDO and the USB module is internal. The rail is also made available on the VUSB pin. There is no internal connection between VUSB and DVCC; they are isolated from each other. This preserves flexibility for the engineer designer to arrange power in a way that is best for a given application.

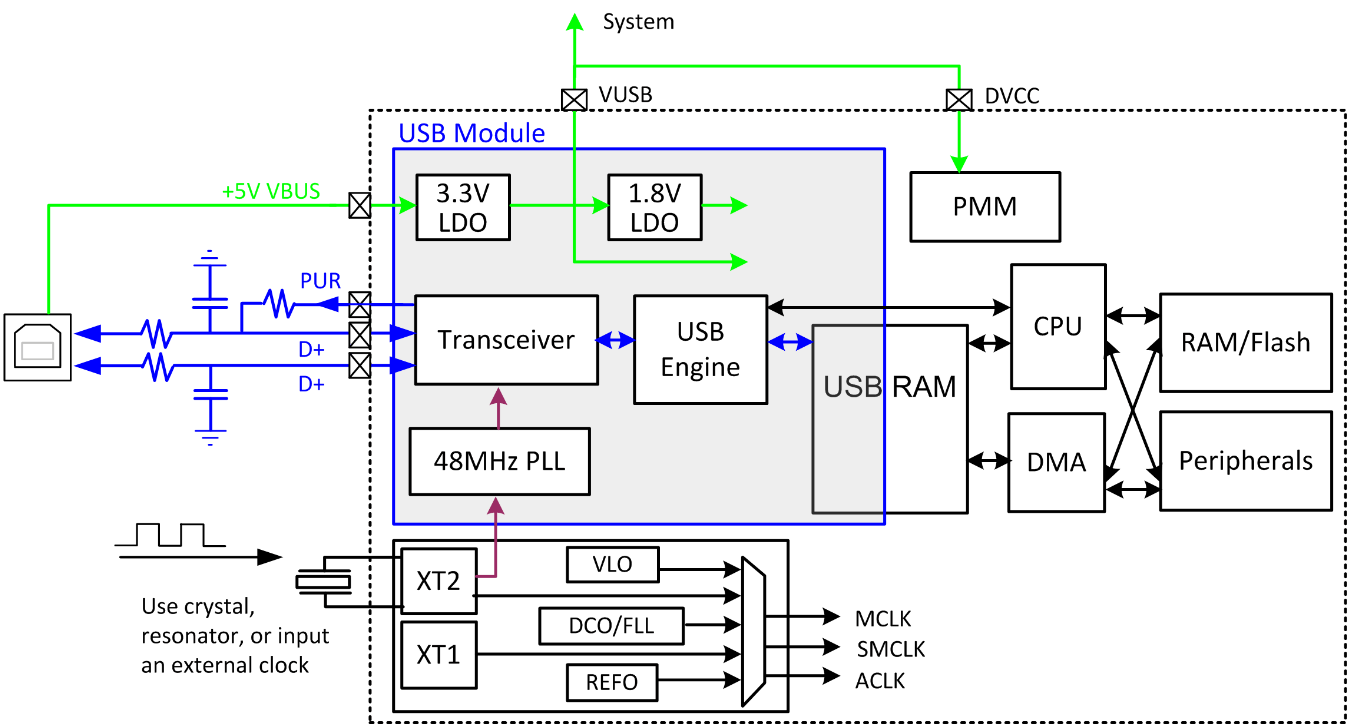

Figure 8. Powering MSP430 From USB Using Internal LDO

4.1.3.2 Unregulated Isolated 8-V Voltage Rail

This is an excellent example how the LMT01 takes away all the pain of building an accurate isolated temperature measurement system, while relaxing the requirements on other supporting blocks. Because the LMT01 has an integrated regulator that provides a stable power supply to its internal circuitry and operates on a floating 2- to 5.5-V (VP–VN) power supply that can vary greatly, unlike other noise-sensitive circuitry, the LMT01 enforces no special requirements such as tight regulation under dynamic load conditions, low noise, and low ripple when designing the isolated power supply.

Some of the basic requirements for unregulated isolated power supply are:

- Input voltage: 5-V nominal UBS VBUS (4.25 to 5.35 V)
- Ramp rate faster than 2.5 ms
- Smaller magnetic component
- Simple, low-cost and area-compliant approach
- Enable and disable feature to put power supply in shutdown mode
- Very low shutdown current

To best demonstrate the performance of this TI Design subsystem, an open-loop isolated push-pull converter topology is chosen because this application does not require a precise output voltage. The open-loop isolated push-pull converter works without feedback circuitry or a signal isolator, which reduces cost and solution size. Due to the low cost and circuit simplicity, the open-loop isolated push-pull converters are commonly used as DC transformers to provide galvanic isolation. For a push-pull converter, the control circuitry consists of only an oscillator along with two gate drivers, which generates two complimentary fixed 50% duty cycle gate signals to drive D1 and D2. The transformer turns ratio is selected to deliver the desired output voltage. To do this job better, this TI Design chooses the SN6505B, a transformer driver designed for low-cost, small form-factor, isolated DC-DC converter utilizing the push-pull topology. The device includes an oscillator that feeds a gate-drive circuit. The gate drive, comprising a frequency divider and a break-before-make (BBM) logic, provides two complementary output signals, which alternately turn the two output transistors on and off.

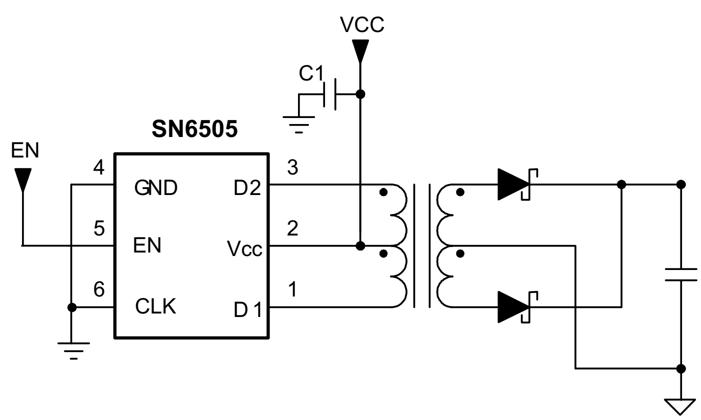

Figure 9. Unregulated Isolated DC/DC Converter Using SN6505

Integrating the technology demonstrated in this TI Design into an end-equipment system may necessitate a different power management configuration. The choice of devices for power management could change, depending on existing input voltage rails. If lower voltage point-of-load rails already exist, then different TI devices for power management can be chosen to suit the conditions of the system (see www.ti.com/power).

4.1.4 EMI Protection

This TI Design has robust protection against electromagnetic interference (EMI) because USB allows the application to have an open connection to the external environment, which could expose the entire system to ESD. Therefore, it is recommended to increase ESD protection on the USB DP, DM, and VBUS lines. This protection should be located as close as possible to the USB connector to reduce the potential discharge path and reduce discharge propagation within the entire system.

This TI Design uses the TPD2E001, a low-capacitance 2-channel ESD protection optimized for high speed applications help save design time. TPD2E001 clean up the application around the interface and maximize protection of system chips while minimizing the impact on signal integrity.

4.2 LMT01 versus Thermistor

There are many reasons why the LMT01 is an ideal digital replacement for thermistors:

1. Figure 10 shows that the LMT01 pulse count output is almost linear over entire temperature range compared to a thermistor. The output ADC code corresponding to thermistor's change in voltage per °C is linear for a limited range and starts to saturate towards the low and high temperatures. This is because the thermistor's resistance versus temperature characteristic is highly exponential.
2. Figure 10 also shows that the LMT01 has a fine resolution of 0.0625°C, which is flat over the entire temperature range. When interfacing with an ADC, the thermistor's nonlinearity gives a reduced resolution towards the extreme temperatures. As a result, the thermistor tends to be less accurate across the entire operating temperature range. However, thermistors can be combined with complex resistive networks to help linearize the curve over a limited temperature range. Note that the resistive networks used with thermistors increase the complexity, cost, and footprint of the overall temperature sensing solution.

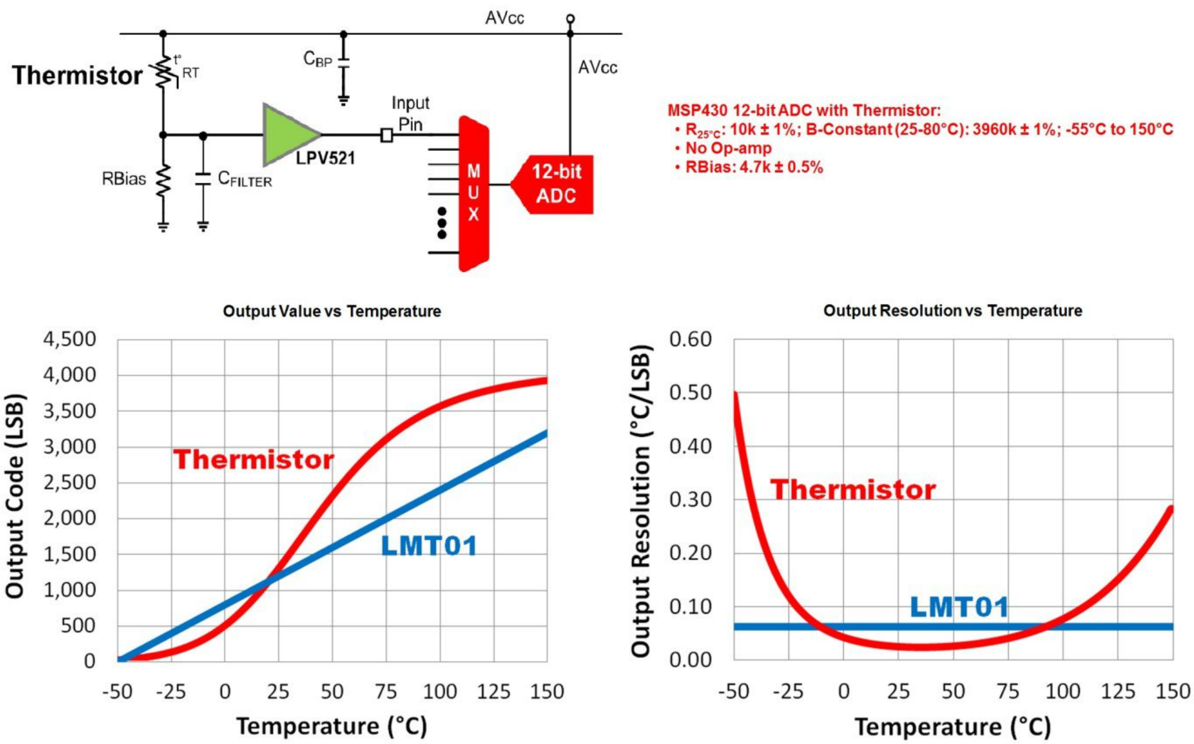

Figure 10. Output Code and Output Resolution versus Temperature

3. Figure 11 shows that the LMT01's consistent low power consumption across temperature minimizes self-heating and system power, further easing the design challenge of temperature monitoring that most of the system engineers encounter when using thermistors. Thermistors have a supply current that varies greatly over temperature. As temperature increases, the NTC thermistor's resistance decreases; this causes the current through the voltage divider network to increase. When the current is high, NTC thermistors can self-heat above the ambient temperature of the environment, resulting in temperature errors.

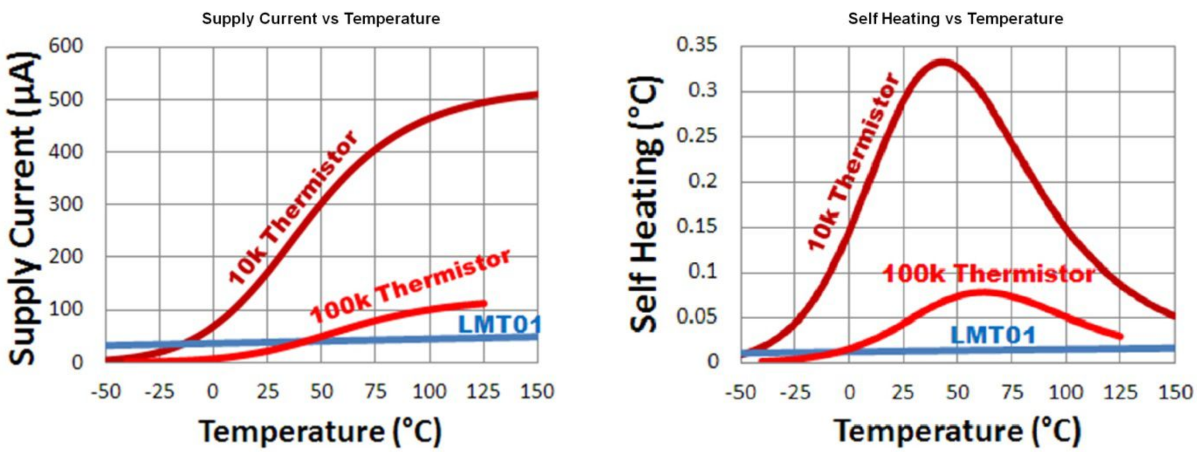

Figure 11. Supply Current and Self Heating versus Temperature

4. Another thing to consider when deciding to use a thermistor is the output impedance. The output impedance of a thermistor is generally higher and varies depending on the temperature. When using an ADC with a thermistor, ensure that the ADC can handle thermistor's source impedance. In some cases, a buffer may be required whereas an easy connection of the LMT01 with the MCU requires minimum components (for example, a simple 5% tolerance resistor).

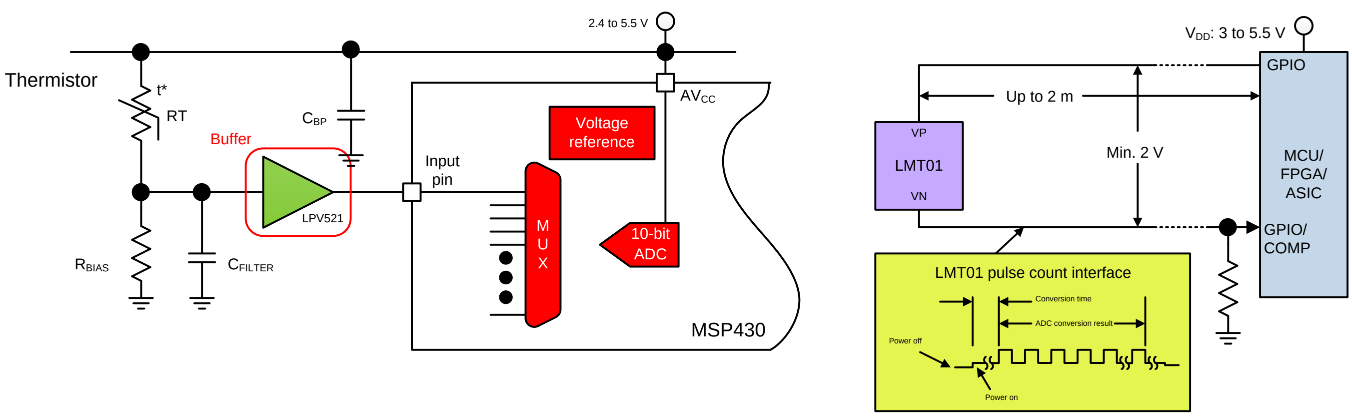

Figure 12. Typical Thermistor and LMT01-Based Circuits

5. One of the most important measurements in any temperature sensor circuit is the accuracy (or error) of the total circuit. When designing a discrete thermistor-based solution, the error from each component must be added to determine the worst-case total error of the measurement whereas the LMT01 accuracy specification includes digitization and quantization errors. System designers do not need to worry about various errors because a single error source makes computing the error budget straightforward.

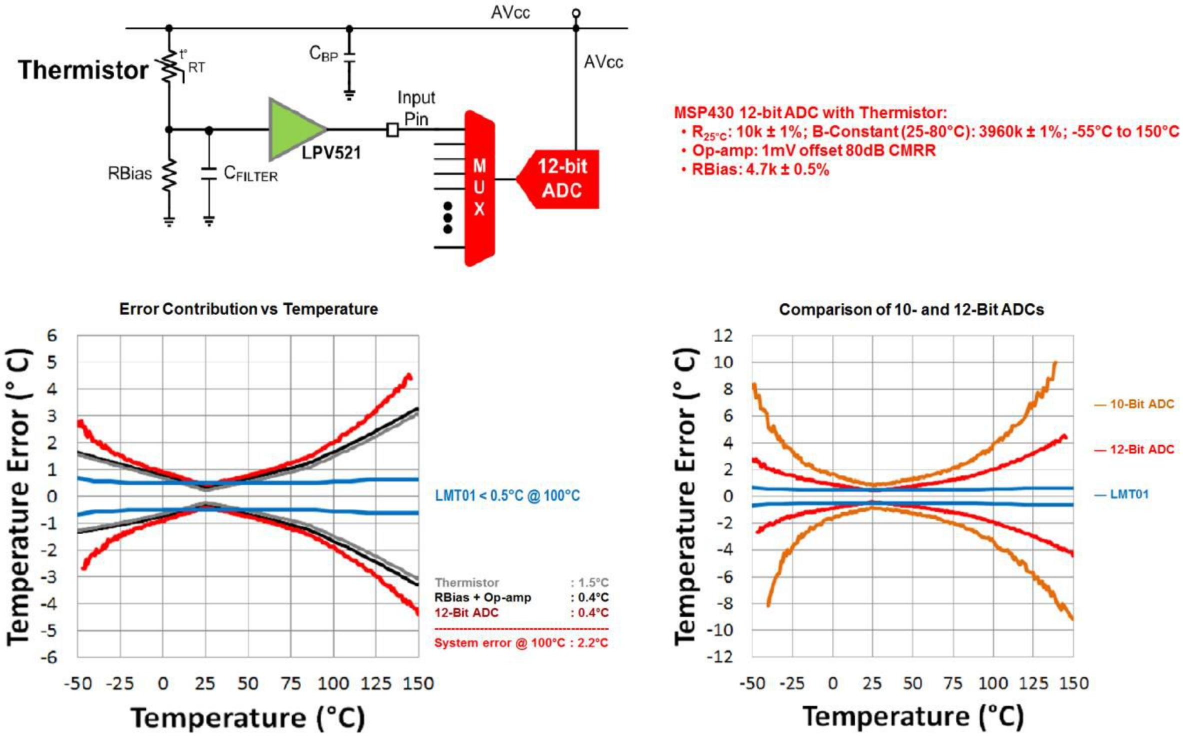

Figure 13. Thermistor and LMT01 Error Contribution versus Temperature

6. Figure 14 compares the accuracy of the LMT01 with the total system accuracy of three different thermistors. The LMT01 provides the best system accuracy over full temperature range that is guaranteed by testing.

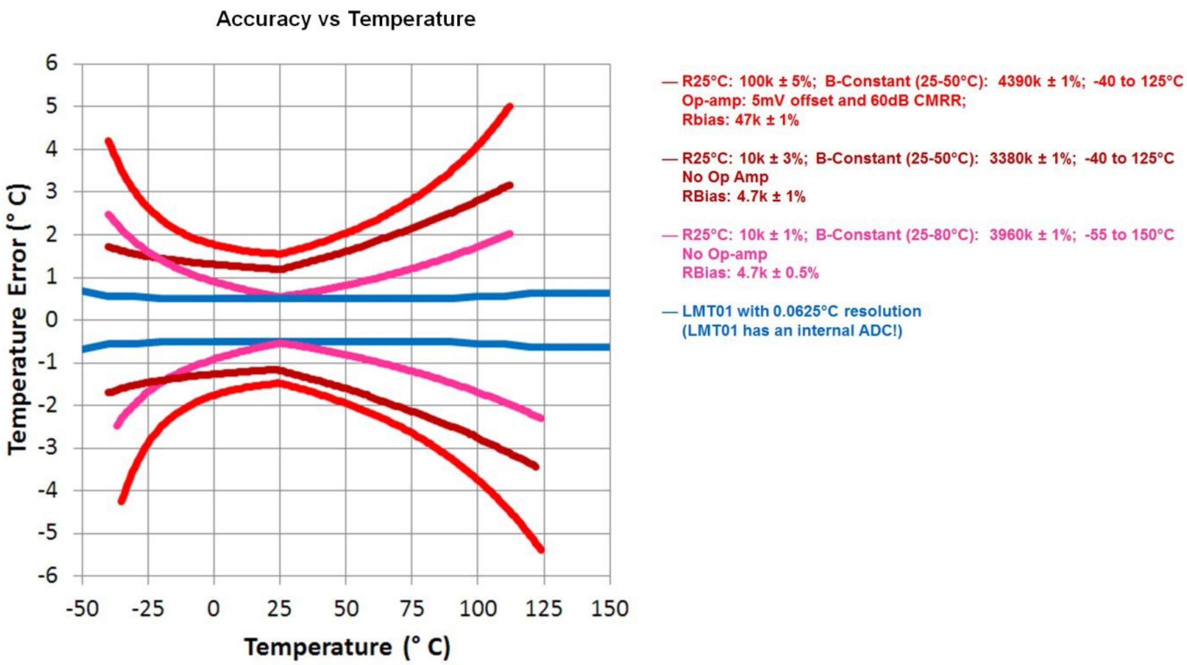

Figure 14. Accuracy versus Temperature

7. The LMT01 is very precise over a wide temperature range and power supply ranges compared to thermistors.

4.3 Circuit Operation

A simple way to transmit analog information across the isolation barrier is to first convert the analog signal into a frequency-type signal such as period, PWM or pulse count. The frequency type signal can then easily be transferred on the other side of the isolation barrier and measured by a microcontroller. The circuit in Figure 15 works on the same principle by taking the advantage of the 2-pin LMT01 digital output IC temperature sensor outputting current pulses that vary depending upon temperature.

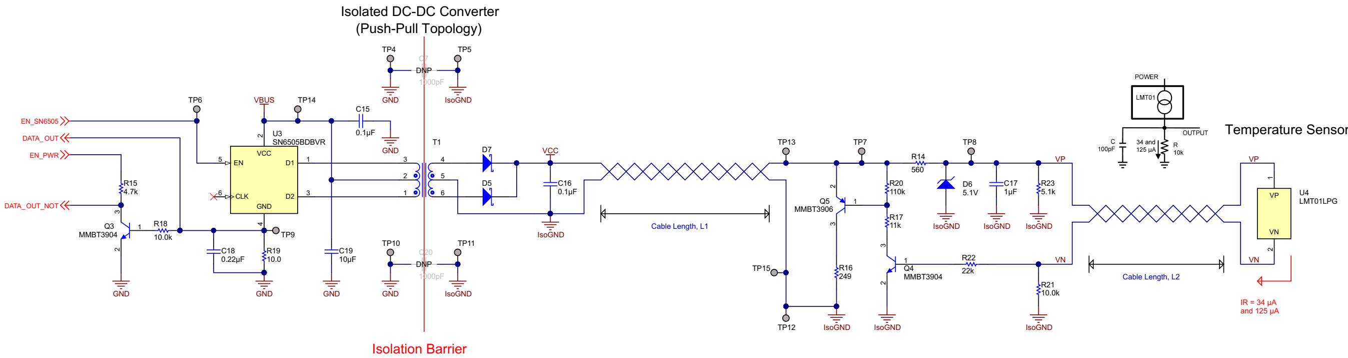

Figure 15. Galvanically Isolated IC Temperature Sensor (LMT01) With Pulse Count Interface

Once enabled from the MCU, the push-pull transformer driver SN6505B drives a low profile 1:2 center-tapped transformer primary from 4.7-V nominal (VBUS–VD3). The transformer's secondary winding followed by rectifier diodes generate an unregulated 8 V, which is subsequently regulated at 5.1 V using a Zener diode for powering the LMT01 temperature sensor. Once the voltage (VP–VN) across the LMT01 is greater than 2.15 V, the LMT01 draws only 34 µA for at most 54 ms while the LMT01 is determining the temperature. Once the temperature is determined, the train of current pulses begins, which typically change from 34 to 125 µA. The individual pulse frequency is typically 88 kHz (nominal). The LMT01 will continuously convert and transmit data when the power is applied approximately every 104 ms (max) as shown in Figure 16. A simple resistor can then be used to convert the current pulses to voltage pulses. With a 10-kΩ (R21) resistor, the output voltage levels range from 340 mV to 1.25 V, typically.

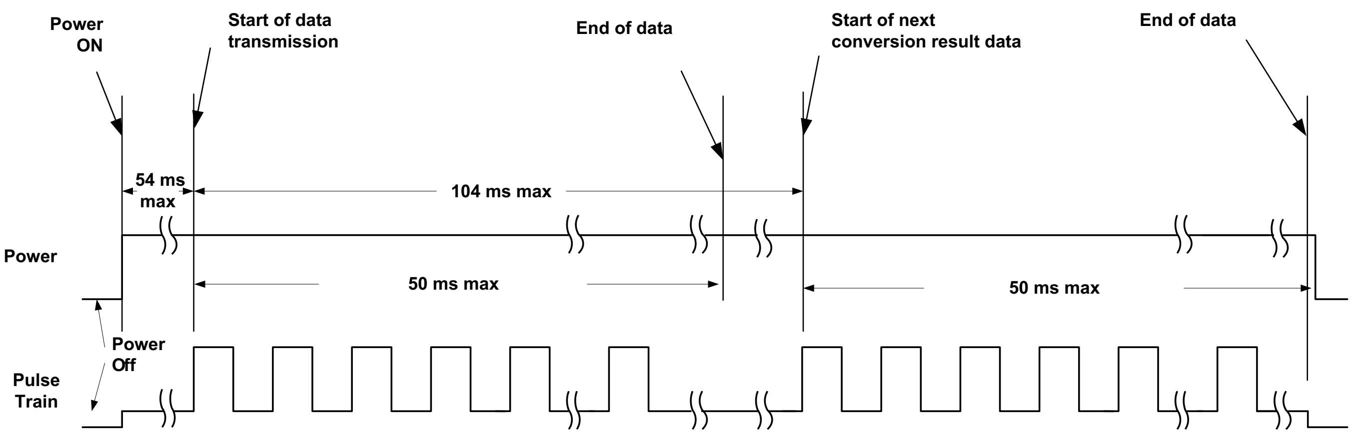

Figure 16. Temperature to Digital Pulse Train Timing Cycle

The output voltage pulse train then drives the base of an NPN transistor (Q4) with a 22-kΩ (R22) base resistor. The Q4 in-turn controls the on-off of PNP transistor (Q5). This means the LMT01 temperature's output indirectly connects or disconnects a 249-Ω (R16) load resistor to the unregulated 8-V supply rail. Therefore, the 249-Ω load resistor suddenly demands a high current during a positive half cycle and very less current during a negative half cycle of the temperature sensor's output. The filter capacitor (C16) at rectifier output on secondary side was intentionally kept very small that places more demands on the input bulk capacitor (C19) at the center tap of the primary for supplying large currents during the fast switching transients on the secondary side due to the LMT01 temperature sensor's output. This makes the pulse frequency of 88 kHz visible on the primary side in the form of supply current, which is then sensed by placing a small shunt resistor (R19) in the ground return path of SN6505B as shown in Figure 17 and Figure 18. The output (DATA_OUT) from R19 and C18 then drives the base of an NPN transistor (Q3) with a 10-kΩ (R18) base resistor to generate a level shifted output (DATA_OUT_NOT). Figure 20 shows the DATA_OUT and DATA_OUT_NOT waveforms. This configuration successfully reproduces the sensor's output on the primary side across isolation as shown in Figure 19. The value of the R19 shunt resistor was chosen such that circuit quiescent current during sensor's conversion time does not turn on Q3. The outputs DATA_OUT and DATA_OUT_NOT are then fed to P1.0/TA0CLK/ACLK, P2.4/TA2.1, and P6.7/CB7/A7 pins of the MSP430 for implementing different pulse counting methods utilizing the MSP430's resources such as GPIO with interrupt, comparator, and timers. This innovative approach isolates the temperature sensor utilizing a single transformer for simultaneous transfer of both power and data across the isolation barrier. The entire circuit draws about 16 mA of average current from VBUS to operate.

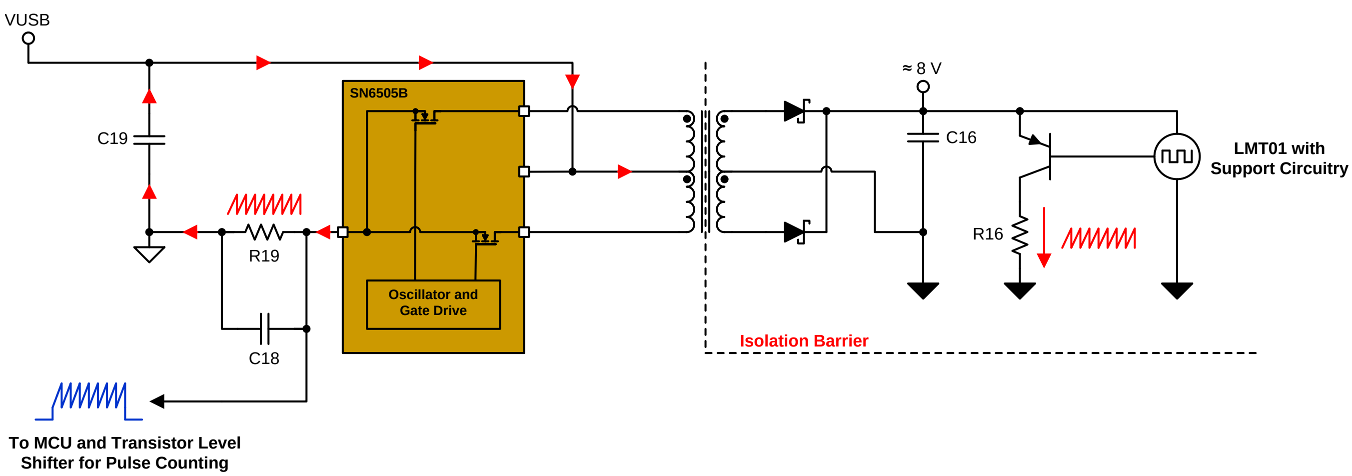

Figure 17. LMT01 Output Current Pulse Train Reproduced on Primary Side Across R19

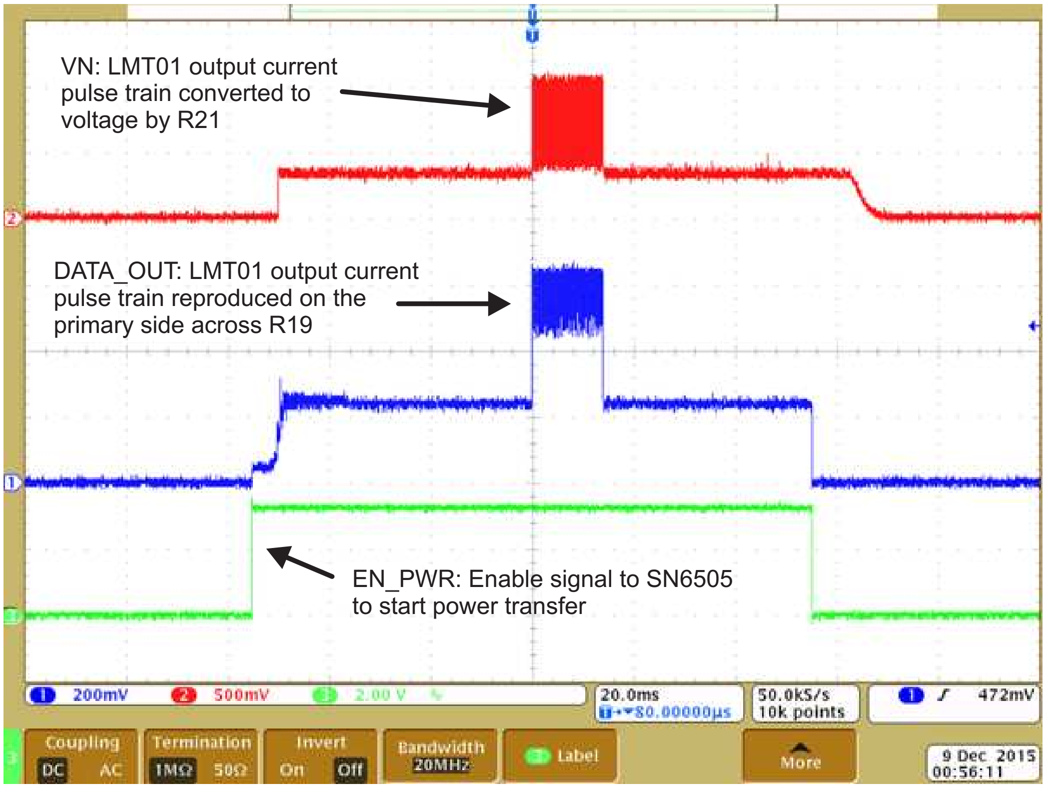

Figure 18. VN (Trace-2), DATA_OUT (Trace-1), and EN_PWR (Trace-3) Waveforms

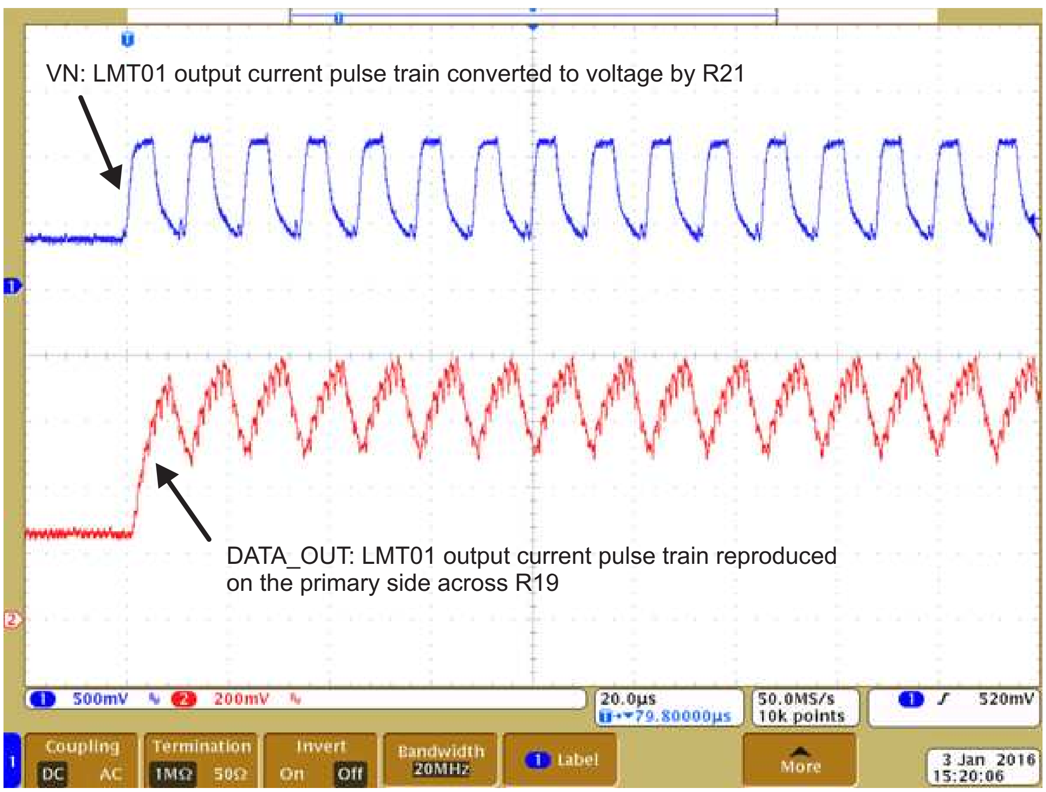

Figure 19. VN (Trace-1) and DATA_OUT (Trace-2) Waveforms

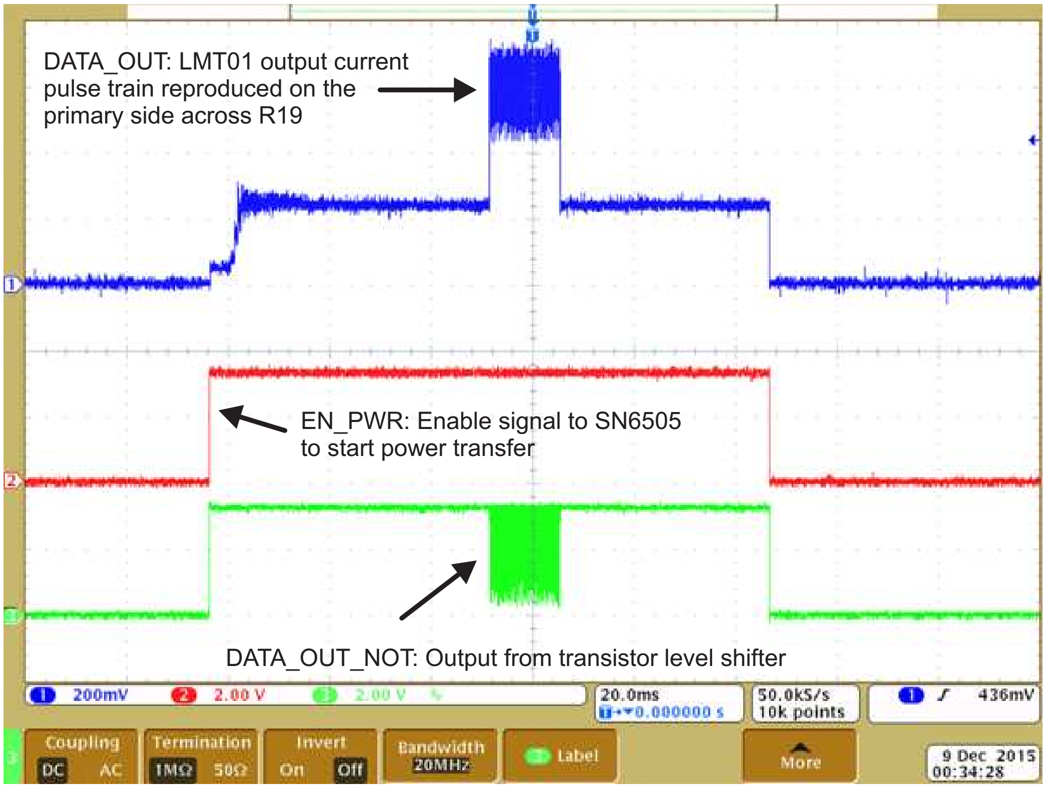

Figure 20. DATA_OUT (Trace-1), EN_PWR (Trace-2), and DATA_OUT_NOT (Trace-3) Waveforms

4.3.1 Transformer Selection

To prevent a transformer from saturation its V-t product must be greater than the maximum V-t product applied by the SN6505. Therefore, the transformer's minimum V-t product is determined through Equation 1:

$$Vt(\min) \geq V_{IN(max)} \times \frac{T(\max)}{2} = \frac{V_{IN(max)}}{2 \times f_{SW(min)}} \tag{1}$$

$$Vt(\min) \geq \frac{V_{IN}(\max)}{2 \times f_{SW}(\min)} = \frac{VBUS(\max) - V_{D3}}{2 \times 363\text{ kHz}} = \frac{5.35\text{ V} - 0.3\text{ V}}{2 \times 363\text{ kHz}}$$

$$Vt(\min) \geq 7\text{ V}\mu\text{s}$$

where

- V_{IN}(max) is the maximum input voltage to the SN6505B
- f_{SW}(min) is the minimum switching frequency of the SN6505B

The transformer selected for this TI Design is 760390015 from Wurth Electronics, which provides V-t product of 11 Vµs with significantly reduced footprint of 10.05 × 6.73 × 4.19 mm. The selected transformer has a working voltage of 400 V_{RMS} and dielectric-withstand voltage of 2500-V AC, which is more than enough for this design.

4.3.2 Sensor Linearization

There are two different methods of converting the pulse count (PC) to a temperature value, first using a first-order transfer function and second using the datasheet's look-up table. This reference design demonstrates the performance using both options.

4.3.2.1 Output Transfer Function

The first-order linear approximation model is as follows:

$$T = \left(\frac{PC \times 256}{4096}\right) - 50°C \quad (2)$$

where

- PC = Pulse count
- T = Temperature reading

NOTE: There is no temperature information in the output frequency of the sensor; only the number of output pulses contains temperature information.

$$\text{Resolution} = \text{Weight of one pulse} = T_{PC+1} - T_{PC} = \left[\frac{(PC+1) \times 256}{4096}\right] - 50°C - \left[\frac{PC \times 256}{4096}\right] + 50°C$$

$$\text{Resolution} = \left[\frac{256}{4096}\right] = 0.0625°C$$

4.3.2.2 Look-up Table

For better accuracy, use the linear interpolation of the value found in Table 2.

Table 2. Compact Pulse Count to Temperature Look-up Table

T1	T2	PC1	PC2	SLOPE
–50	–40	26	181	0.064516
–40	–30	181	338	0.063694
–30	–20	338	494	0.064103
–20	0	494	808	0.063694
0	10	808	966	0.063291
10	50	966	1602	0.062893
50	60	1602	1762	0.062500
60	90	1762	2245	0.062112
90	130	2245	2893	0.061728
130	140	2893	3057	0.060976
140	150	3057	3218	0.062112

Figure 21 shows the output transfer function using the first-order equation (blue line) and using linear interpolation of look-up table values (red line). The LMT01 output transfer function as described by the LUT appears to be linear, but upon close inspection it can be seen that it is not truly linear. Figure 21 also shows the error introduced by the first-order linear approximation model considering look-up table values as baseline.

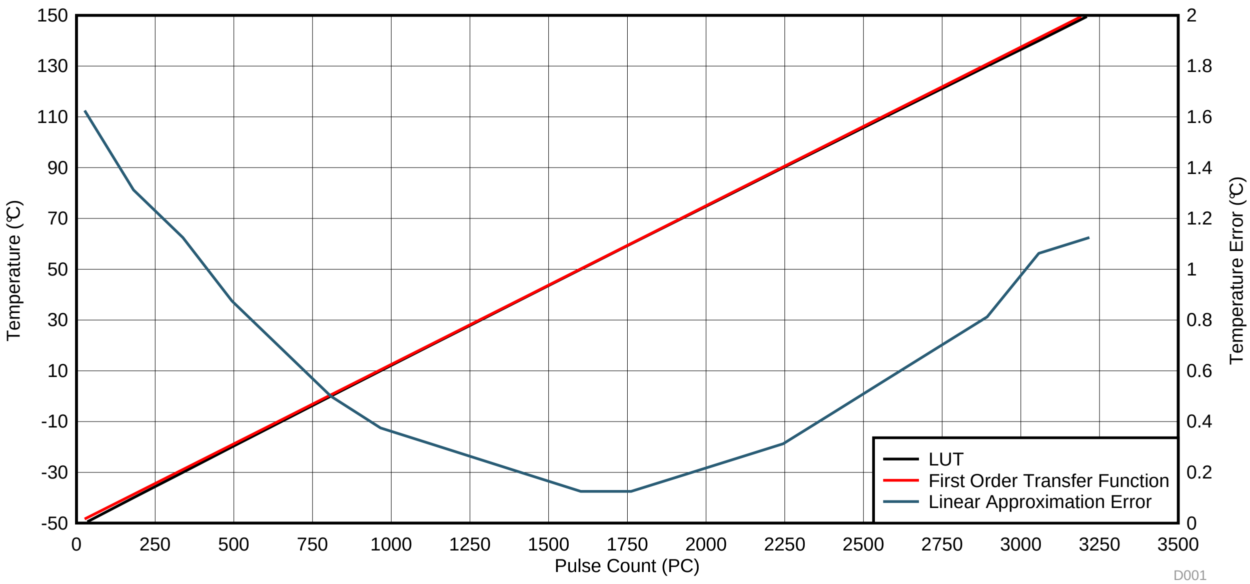

Figure 21. LMT01 Output Transfer Function and Accuracy With Linear Approximation

4.3.3 Self-Heating

More or less, all temperature sensors exhibit a phenomenon known as self-heating. The internal self-heating is a byproduct of electrical current flow in the electronic device during its operation. Dissipating power in the temperature sensor causes its temperature to rise above that of the surrounding environment. Any difference between the temperature of the sensor and the environment produces a temperature measurement error or uncertainty. Minimizing the temperature measurement uncertainty thus requires balancing the uncertainties due to self-heating. The thermal resistance junction-to-ambient ($R_{\theta JA}$) is the parameter used to calculate the rise of a device junction temperature (self-heating) due to its average power dissipation. The average power dissipation of the LMT01 is dependent on the temperature it is transmitting as it affects the output pulse count and the voltage across the device. Equation 3 is used to calculate the self-heating in the LMT01's die temperature (T_{SH}).

$$T_{SH} = \left[\left(I_{OL} \times \frac{t_{CONV}}{(t_{CONV} + t_{DATA})} \times V_{CONV}\right) + \left(\left[\left(\frac{PC}{4096} \times \frac{(I_{OL} + I_{OH})}{2}\right) + \left(\frac{(4096 - PC)}{4096} \times I_{OL}\right)\right] \times \frac{t_{DATA}}{(t_{CONV} + t_{DATA})}\right) \times V_{DATA}\right] \times R_{\theta JA} \quad (3)$$

where

- T_{SH} is the ambient temperature
- I_{OL} and I_{OH} are the output low and high current level, respectively
- V_{CONV} is the voltage across the LMT01 during conversion
- V_{DATA} is the voltage across the LMT01 during data transmission
- t_{CONV} is the conversion rate
- t_{DATA} is the data transmission time
- PC is the output pulse count
- $R_{\theta JA}$ is the junction to ambient package thermal resistance

With a temperature range of –50°C to 150°C, a V_{CONV} of 4.76 V was used for the self-heating calculation. As can be seen in the curve in Figure 22, the average self-heating changes linearly over temperature because the number of pulses increases with temperature. A negligible self-heating of about 42 m°C is observed at 150°C with continuous conversions. If temperature readings are not required as frequently as every 100 ms, self-heating can be minimized by shutting down power to the part periodically thus lowering the average power dissipation as shown in Figure 23. Be sure to use a power down wait time of 50 ms, at minimum, before the device is turned on again.

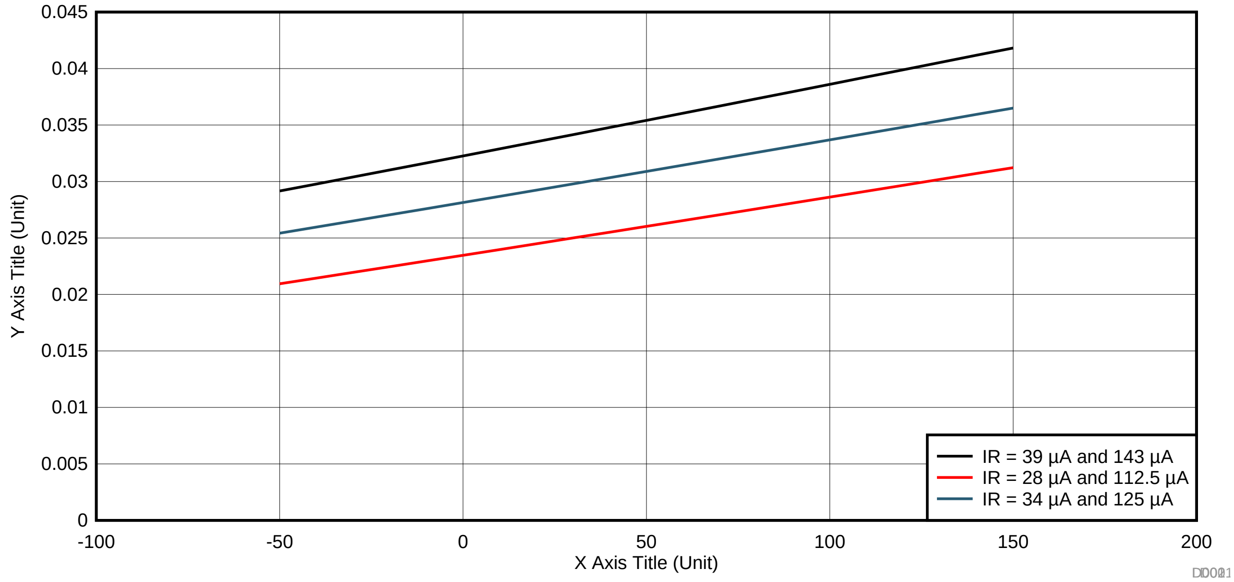

Figure 22. LMT01 Self-Heating

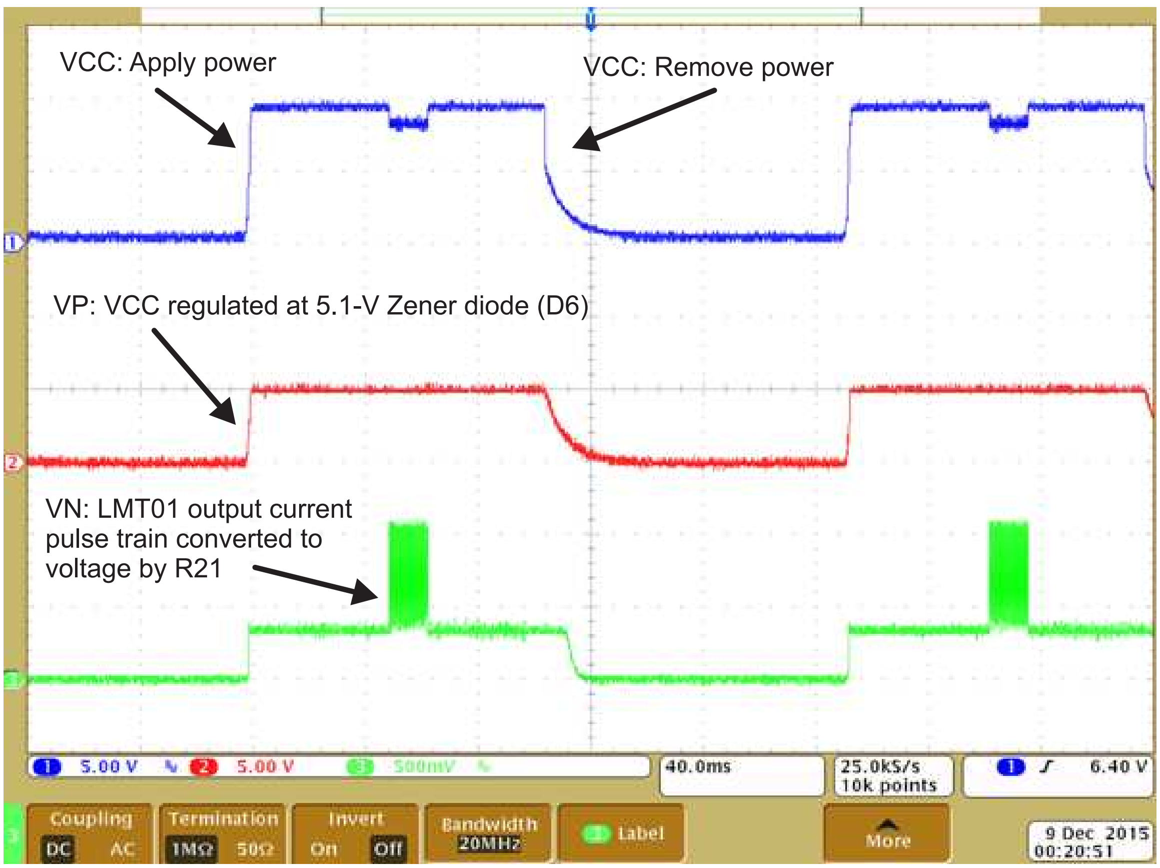

Figure 23. VCC (Trace-1), VP (Trace-2), and VN (Trace-3) Waveforms

4.4 Wired Temperature Sensor Probes Using LMT01

Remote temperature sensors require some form of packaging to allow them to withstand conditions such as rough handling, vibration and moisture. Many temperature sensors are so fragile that even normal installation can be harmful for them. The main purpose of the housing is to protect the sensing element. A rugged, moisture resistant temperature sensing probes and assemblies have proven extremely effective in high moisture environments and quite commonly used in HVAC applications such as chillers, heat pumps, packaged terminal air conditioners (PTACs), boilers, furnaces, air handlers, zone controls, and many other heating and cooling products. Its low cost, tiny package (TO-92/LGP), and 2-pin interface make the LMT01 IC temperature sensor a best choice for wired-sensor probe assemblies benefitting in building indoor and outdoor temperature measurement applications. Figure 24 shows some of the wired-sensor probe assemblies, which were built using the LMT01 having form-factors fully compatible with RTD or thermistor-based temperature probes.

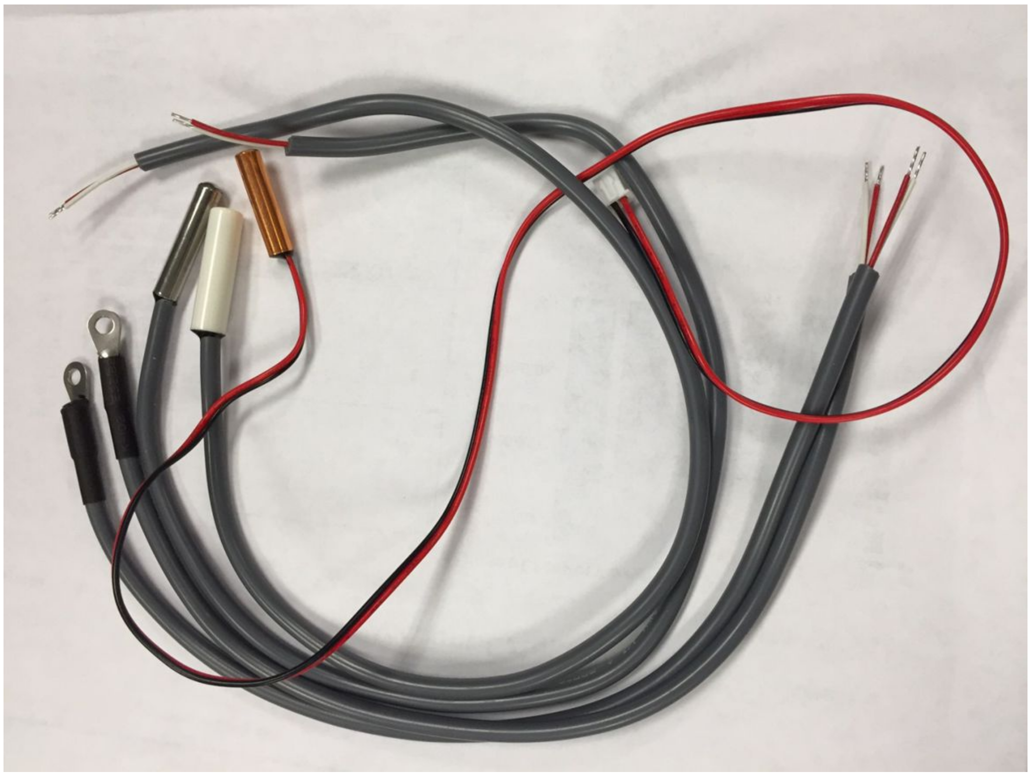

Figure 24. LMT01 IC Temperature Sensor Based Wired-Probe Assemblies

4.5 Sensor Wiring Diagnostics

Knowing the amount of current being delivered to a sensor can be useful in wiring fault detection and protection. The current being delivered can be easily monitored by adding a sense resistor in series with the circuit. By nature, this circuit already uses a sense resistor in the primary circuit for its normal operation. This capability can also be used to detect open or short circuits caused by wiring or connector failures and can timely trigger a preventive action. Therefore, this novel circuit allows simple and reliable diagnostics of system wiring faults without requiring any additional hardware.

The default firmware does not support the sensor diagnostic feature. However, by writing a small code on top of your application as per directions in this section can perform continuous on-line sensor diagnosis without running a separate diagnostic cycle. This may save production costs, and hours of troubleshooting time, by letting you know when a problem occurs and its type.

4.5.1 Open Circuit Fault Detection

Figure 25 shows an example of an open circuit fault. If there is an open circuit connection on the sensor leads or wires, this does not complete the circuit. The sensor does not see any supply voltage between the VP and VN pins; therefore, the sensor cannot output the current pulse train. As a result, the MCU receives no pulses for counting, which can be easily detected in software. If pulses are not received consistently for a few cycles, it may be declared as a sensor open circuit fault.

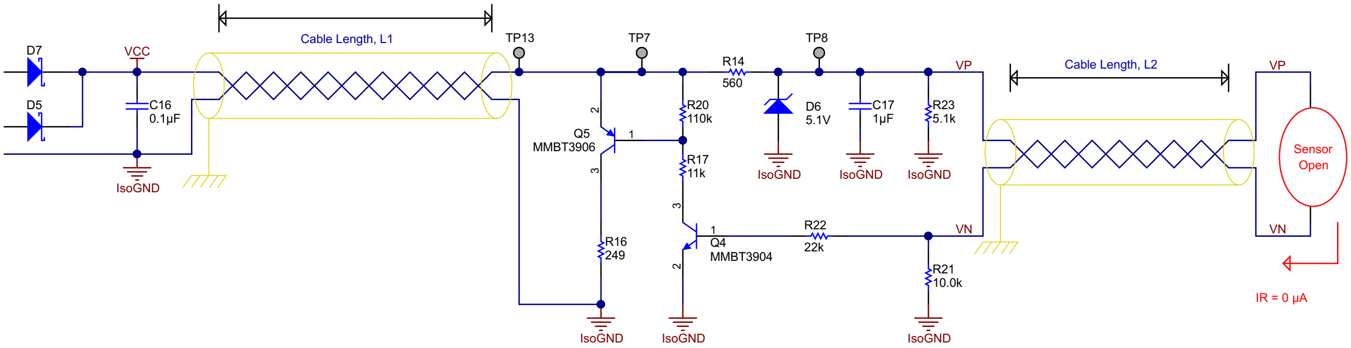

Figure 25. Open Circuit Connection on Sensor Leads

4.5.2 Short Circuit Fault Detection and Protection

Figure 26 shows an example of a short circuit fault between the sensor leads. In this case, 5.1 V (VP) starts driving the NPN transistor (Q4) directly. This connects the 249-Ω (R16) resistor forever to the 8-V rail demanding high current from primary, which causes voltage drop across R19 sufficient to drive Q3. The conduction in Q3 makes DATA_OUT_NOT signal to go low as shown in Figure 27. During normal operation as shown in Figure 20, the DATA_OUT_NOT signal remains high for about 54 ms (conversion time) after applying EN_PWR signal to the SN6505. The DATA_OUT_NOT signal going low in the initial 54 ms indicates a short circuit fault, which can be easily detected in the software. Once the short circuit is detected, the EN_PWR signal to the SN6505 can be immediately disabled from the MCU as a preventive measure.

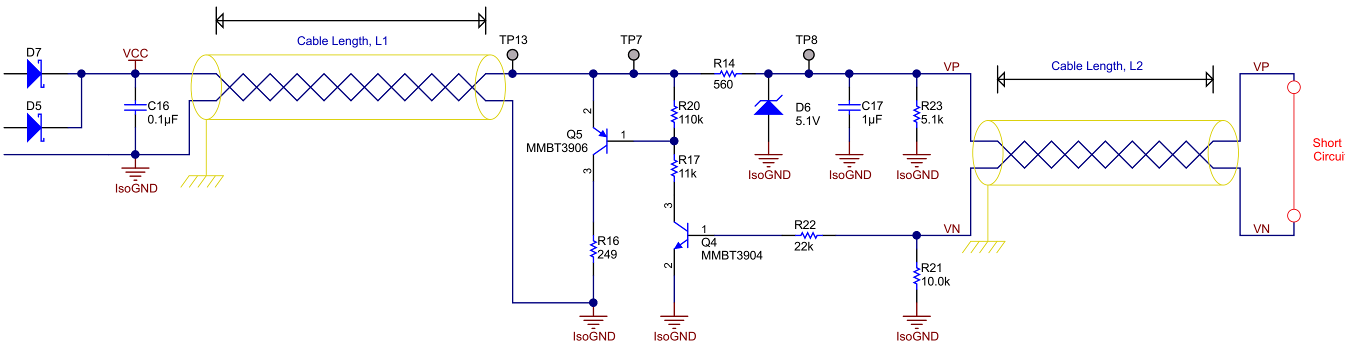

Figure 26. Short Circuit Between Sensor Leads

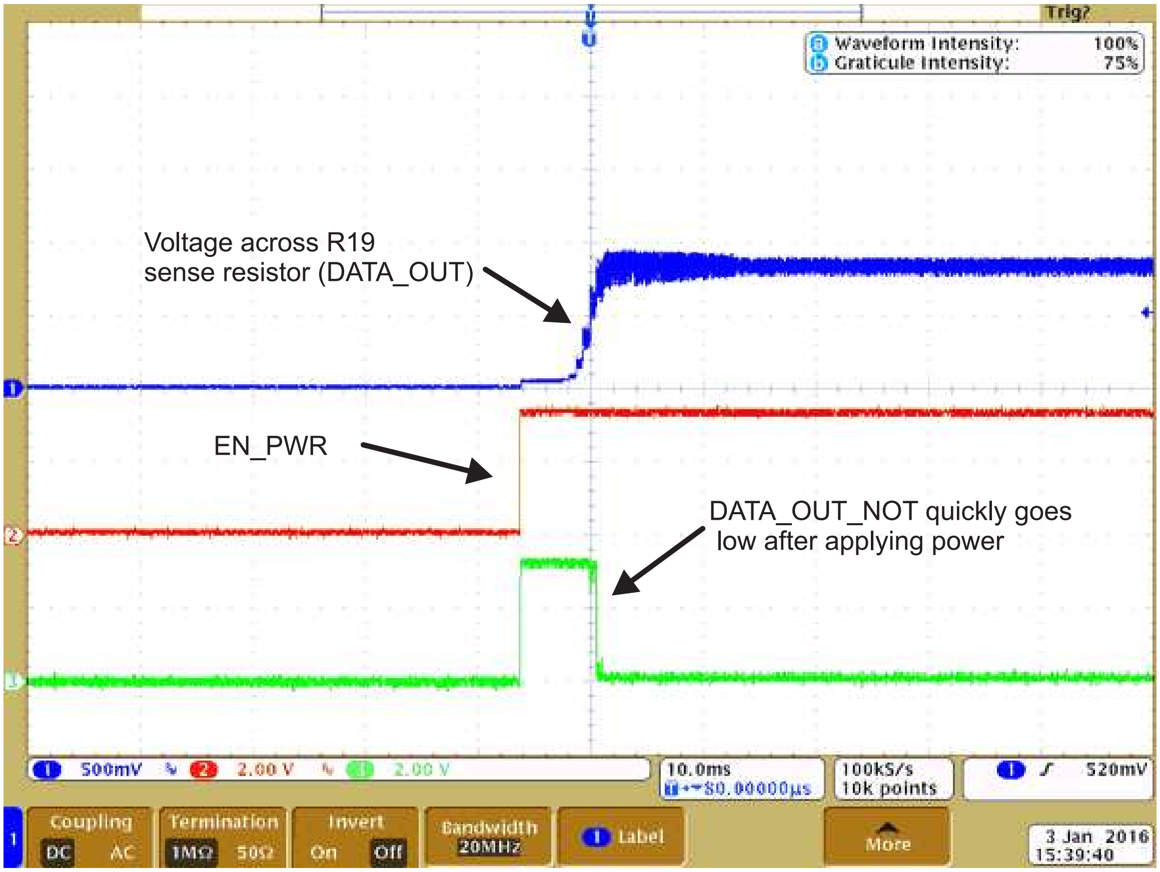

Figure 27. Circuit Behavior During Short Circuit Fault Between Sensor Leads

Figure 28 shows another example of short circuit in the 8-V rail wiring. In this situation, a dead short in the 8-V rail suddenly puts an excessive current demand on the primary. The SN6505 has a current limiting function, which gets activated at 1.7 A; this is perhaps too high for an end-equipment application. The voltage drop across R19 starts ramp-up. As soon as this voltage goes slightly higher than 0.7 V, the conduction in Q3 starts, which immediately pulls DATA_OUT_NOT signal low. All this happens much before the short circuit current shoots to a very high value and triggers the SN6505 current limiting function. Just like the previous situation, the DATA_OUT_NOT signal going low in the initial 54 ms indicates a short circuit fault, which can be easily detected in the software. Once the short circuit is detected, the EN_PWR signal to the SN6505 can be immediately disabled from the MCU as a preventive measure.

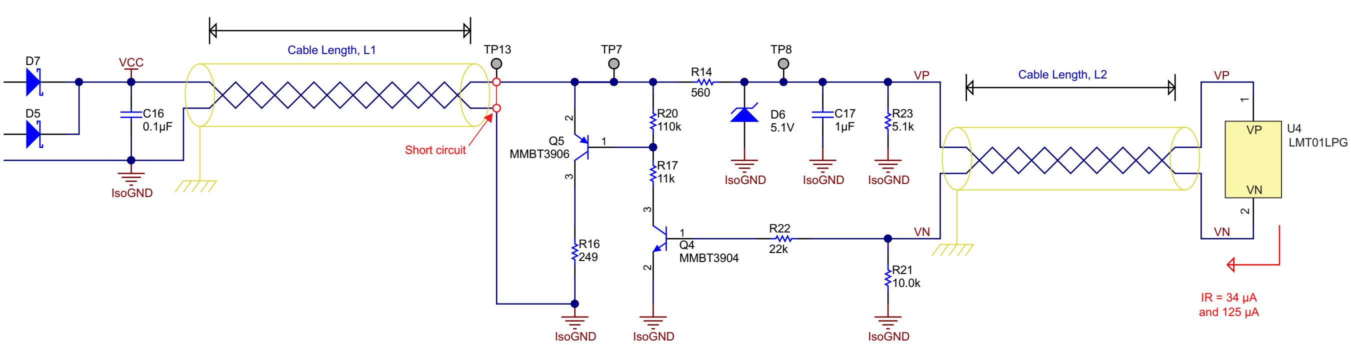

Figure 28. Short Circuit in 8-V Rail Wires

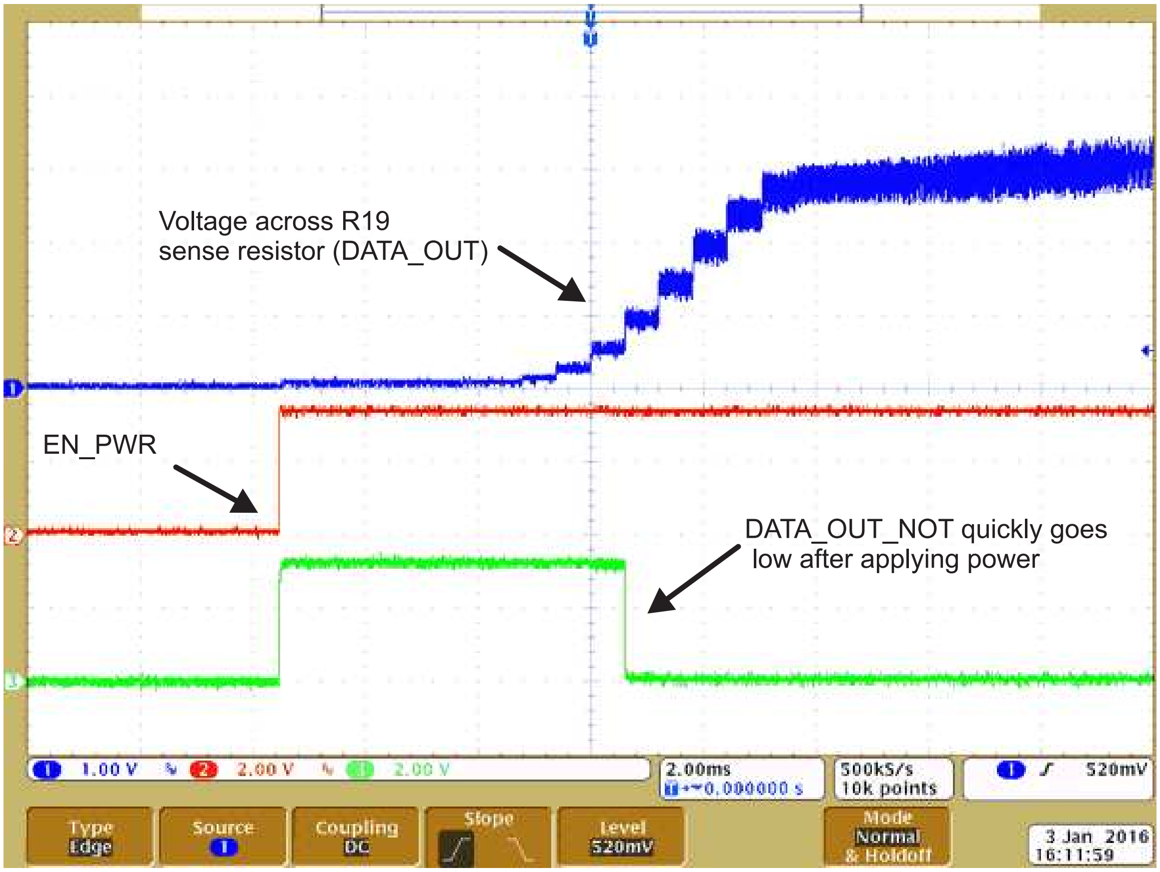

Figure 29. Circuit Behavior During Short Circuit Fault in 8-V Rail

5 Getting Started

5.1 Hardware Overview

This TI Design hardware allows users to evaluate the performance of the LMT01 2-pin digital temperature sensor (U4) located on the extreme right side of the board. All of the components such as ICs (TPD2E001, MSP430F5528, SN6505B, and LMT01), USB connector, transformer, and others are placed on the top side of the PCB. There are test points located on the PCB for most of the signal lines as well as the power nodes. The hardware comes in a convenient USB stick form factor package with an onboard MSP430F5528 (U1) MCU that interfaces with both the host computer and the galvanically isolated LMT01. The hardware also comes with perforation at three locations on the PCB as shown in Figure 30. The first perforation (breakout-1) separates the MCU side of the board from rest of the sections that allows user to connect a different MCU board for temperature measurement.

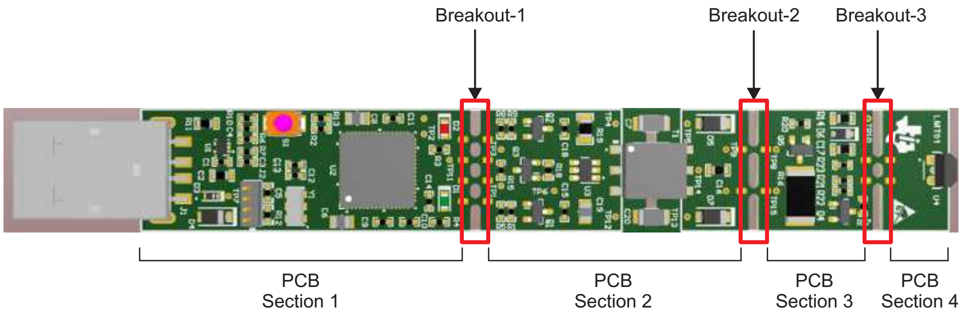

Figure 30. TIDA-00752 TI Design Subsystem Hardware

5.2 Modification for Remote Temperature Sensing

This TI Design comes with three perforated slots where the user can snap apart PCB sections as desired. Snap off the PCB at breakout-2 and then solder wires between the snapped off sections (Section #1+2 and Section #3+4) for remote temperature measurements as shown in Figure 31.

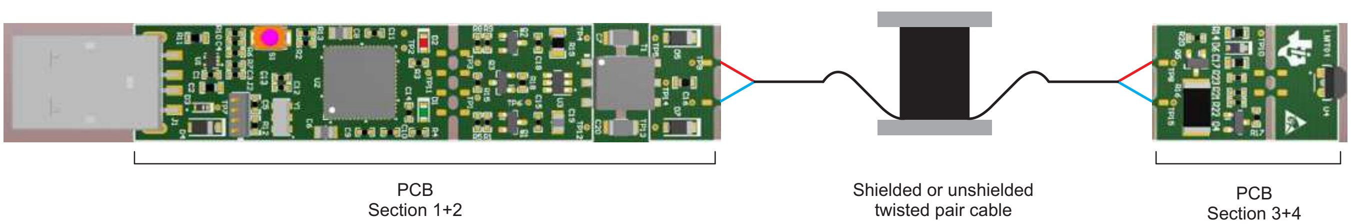

Figure 31. Remote Temperature Sensing

This TI Design uses a 30-m long low-capacitance 24 AWG shielded twisted pair cable (Part Number: 8641 060100) from Belden for testing.

5.3 Software Overview

The 2-Wire Galvanically Isolated IC Temperature Sensor with Pulse Count Interface reference design reuses the LMT01EVM's MSP430 firmware and GUI. The computer runs the GUI software that communicates with the MSP430 on the TI Design over a USB connection. The MSP430 firmware implements 12 methods of measuring the output pulse train from the LMT01. The GUI software allows users to select any measurement method for their application. Figure 32 shows all 12 pulse train measurement methods with their actual code sizes. Figure 33 shows the flow diagram for one of the method which was mostly used during the testing.

The LMT01EVM GUI software is available in the LMT01EVM product folder on the TI website (www.ti.com). For more information about installing LMT01EVM's GUI software, GUI descriptions, loading firmware into board, and implementations of 12 different pulse train measurement methods, see the *LMT01EVM User's Guide* (SNIU027).

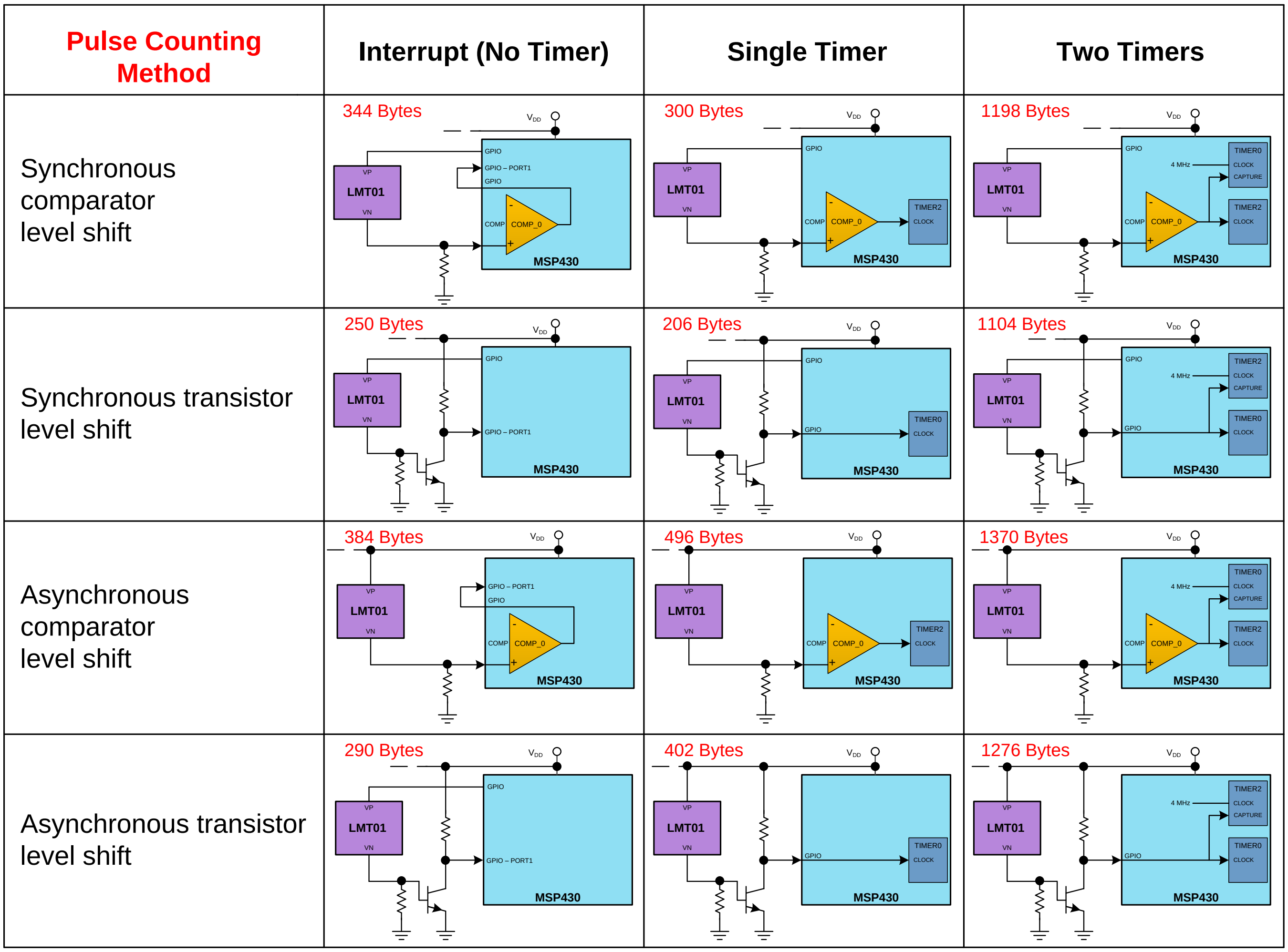

Figure 32. Different Pulse Counting Methods and Code Size

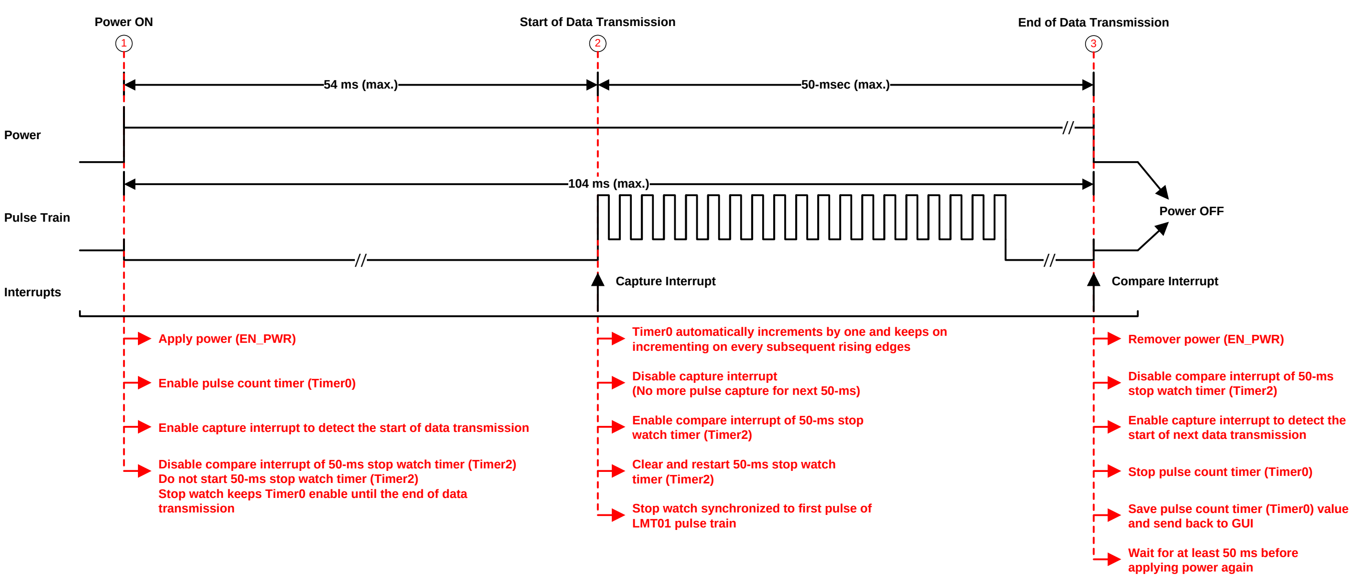

Figure 33. Flow Diagram for Two Timers Synchronous Transistor Mode Pulse Counting Method

6 Test Data

NOTE: Unless otherwise noted, the test data in the following sections were measured with the system at room temperature.

NOTE: All of the measurements in this section were measured with calibrated lab equipment.

6.1 Overview

Some of the functional and environmental testing was also performed to verify how the reference design acts in different environments. The following subsections describe the test setup, procedures, and test data with some explanation.

6.2 Power Supply Ramp Rate

Since the LMT01 is only a 2-pin device, the power pins are common with the signal pins. As a result, the LMT01 has a floating supply that can vary greatly. The LMT01 has an internal regulator that provides a stable voltage to internal circuitry. Power supply ramp rate can affect the accuracy of the first result transmitted by the LMT01. Therefore, it is recommended that either the power supply be within the final value before a conversion is used or that ramp rates be faster than 2.5 ms. The measures rise time of the LMT01 power supply (VP) is 1.158 ms as shown in Figure 34.

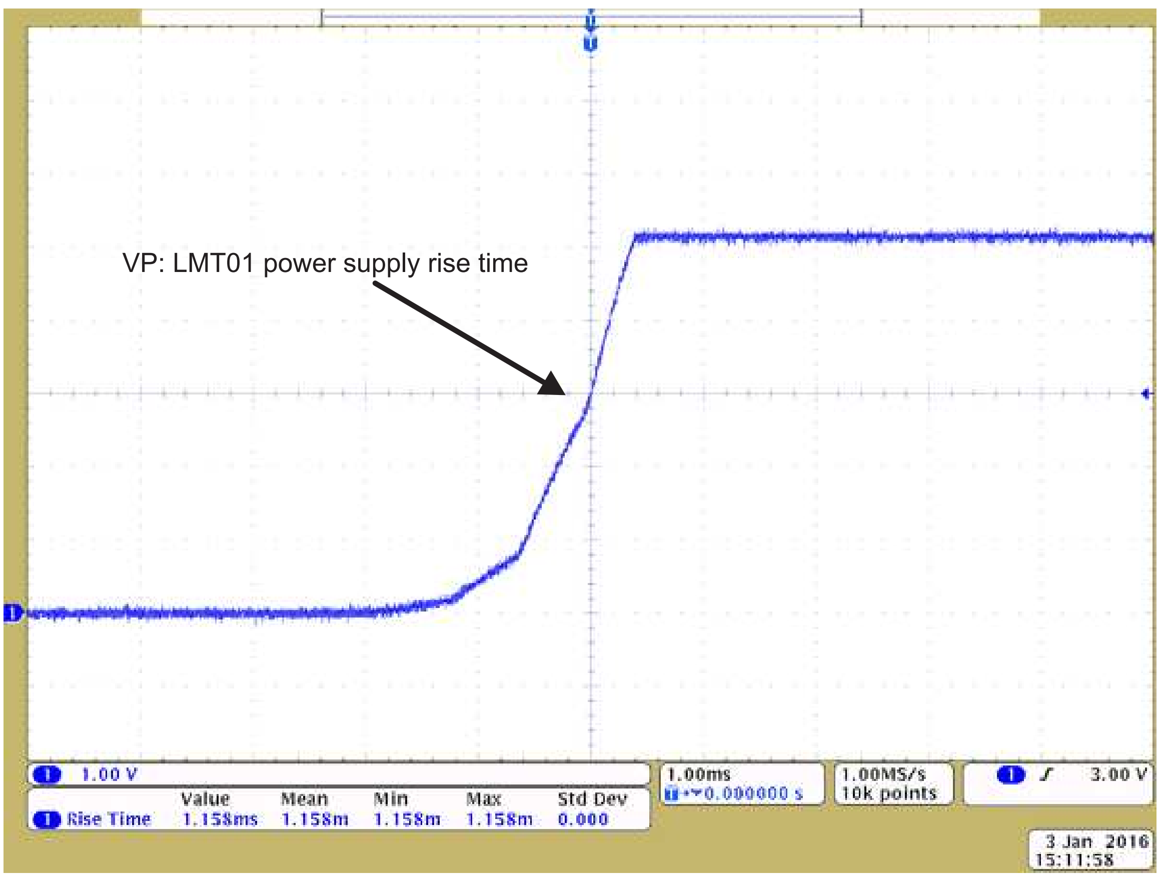

Figure 34. LMT01 Power Supply Rise Time

6.3 Test for No Missing Pulses

Other than the LMT01, the only place that can introduce error in the measurement is pulse counting in the MCU. If the MCU is unable to detect even a single pulse, it adds an error of 0.0625ºC in the measurement. Therefore, it is really important to make sure that the interface is robust and the MCU does not miss any pulse generated by the LMT01.

However, it is difficult to test for any missing pulses with the LMT01 connected in the circuit because it is unknown exactly how many pulses the LMT01 is going to transmit. The simplest way to test this is to remove the LMT01 from circuit and connect an arbitrary function generator as shown in Figure 35. This reference design uses AFG3051C Arbitrary Function Generator from Tektronix to simulate the LMT01 pulse output functionality. Now change these functional generator settings to generate a repetitive burst of square waveform with a known number of pulses:

- Frequency: 88 kHz
- Amplitude: V_{OH} = 1.25 V and V_{OL} = 0.34 V (Similar to the voltage levels produced by the LMT01 across a 10-kΩ resistor)
- Function: Square waveform
- Period: 104 ms
- Pulses (PC): Varied from 32 to 3200

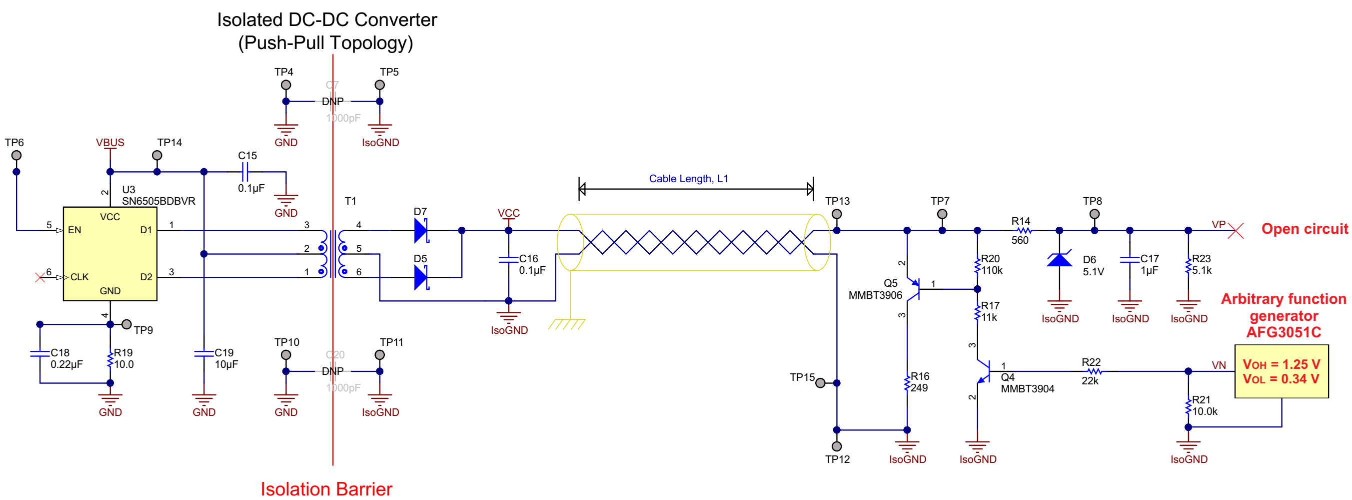

Figure 35. Test Setup for No Missing Pulses

Now the pulse count was increased from 32 to 3200 in increments of 32 pulses, representing a temperature between –50ºC to 150ºC. The LMT01EVM's GUI was used to log the pulses counted by the MCU for about 5 minutes at each set pulse count. At the end of the test, the log files were verified and it was found that MCU does not miss any pulse.

6.4 Oil Bath Testing

An excellent way to test the overall accuracy of this TI Design is to place the LMT01 temperature sensor in a very stable, uniform, and accurate temperature source and sweep its temperature. A calibrated thermal oil bath is a good temperature source for this test. The experimental setup for this test is shown in Figure 36. This experiment is specifically intended to reveal inaccuracies in the LMT01 temperature sensor. The rest of the circuitry is held at a relatively constant ambient temperature (room temperature) with no temperature forcing. The temperature of thermal oil bath is varied from –35ºC to 150ºC in increments of 5ºC with a soaking time of 30 minutes at each temperature, followed by temperature measurement of the LMT01. The temperature readings of the LMT01 are recorded to find out the temperature error from the set temperature in thermal oil bath. Figure 37 and Figure 38 show the plot of temperature errors against the thermal oil bath temperature obtained in this experiment when using LUT linear interpolation and first-order transfer function methods, respectively. The results in Figure 37 indicate approximately 0.25ºC of error over the temperature range from –35ºC to 150ºC. This result is well within the guaranteed accuracy limits of the LMT01 as specified in the datasheet. The results in Figure 38 indicate an approximately 0.25ºC of error for a short range of temperature from 15ºC to 100ºC and around 1.35ºC over the complete temperature range of –35ºC to 150ºC.

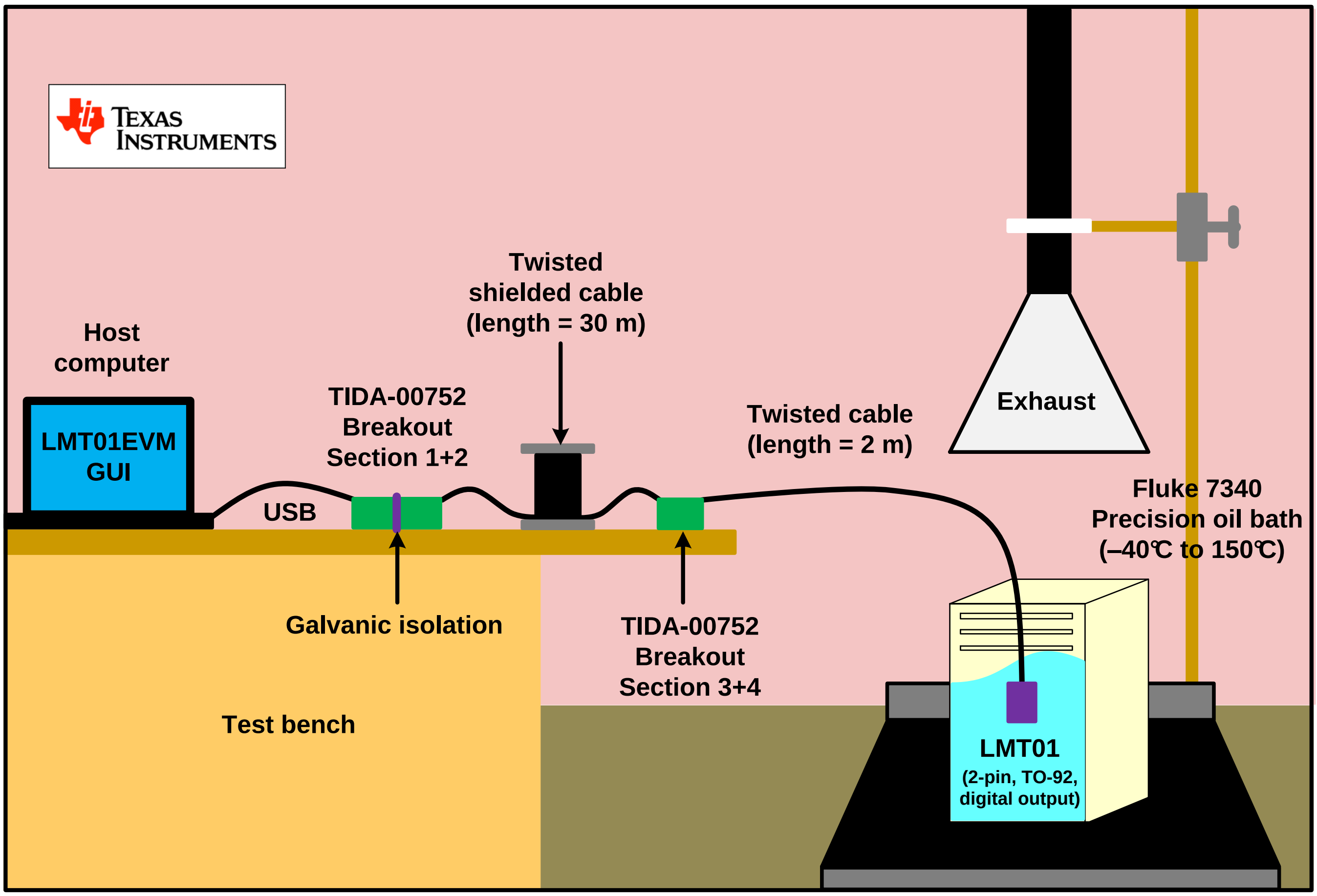

Figure 36. Oil Bath Test Setup

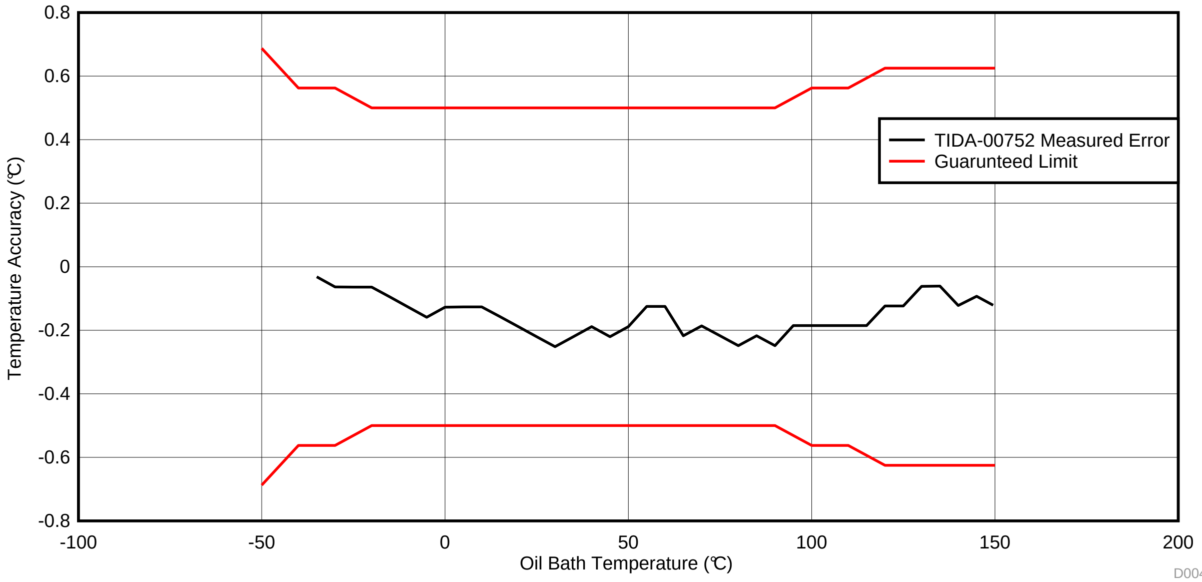

Figure 37. LMT01 Accuracy When Using LUT Linear Interpolation

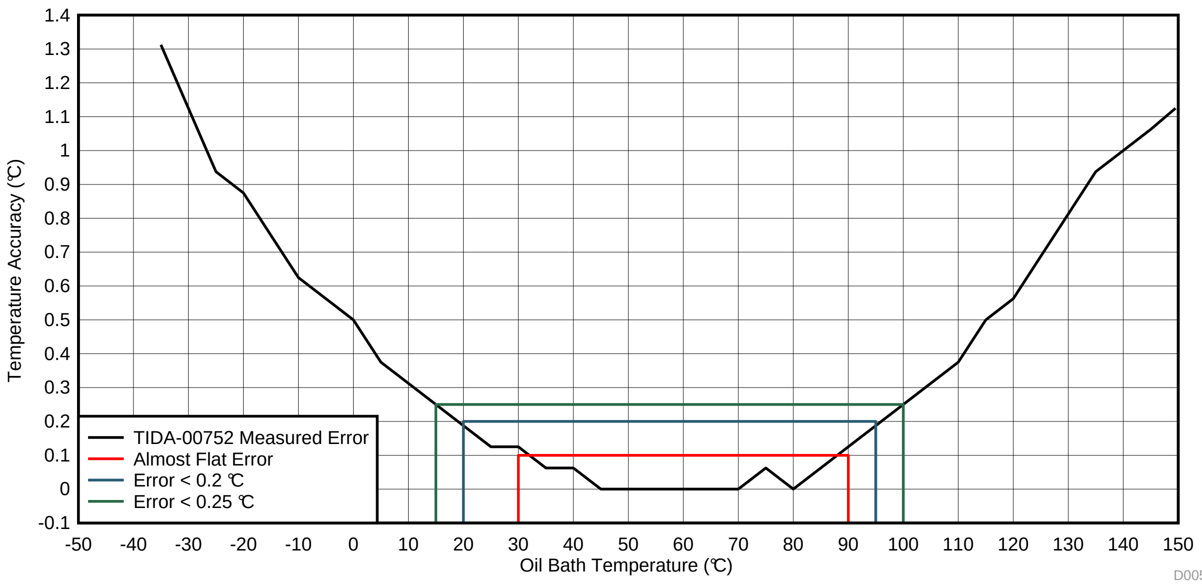

Figure 38. LMT01 Accuracy When Using First-Order Transfer Function

When compared, the improved performance when using the LUT linear interpolation method can clearly be seen. For a limited temperature range of 25°C to 90°C, the error shown in Figure 38 is pretty flat and thus the linear equation provides good results. For a wide temperature range, use linear interpolation and the LUT.

6.5 IEC61000-4-4 EFT

This TI Design was characterized through pre-compliance test for EFT using a 30-m long shielded twisted pair cable.

Table 3. Criteria and Performance as Per IEC61131-2

CRITERIA	PERFORMANCE (PASS) CRITERIA
A	The system shall continue to operate as intended with no loss of function or performance even during the test.
B	Temporary degradation of performance is accepted. After the test, the system shall continue to operate as intended without manual intervention.
C	During the test, loss of functions accepted, but no destruction of hardware or software. After the test, the system must continue to operate as intended automatically, after a manual restart, powering off, or powering on.

For the IEC 61000-4-4 pre-compliance test, the system was powered and the temperature readings were recorded through a USB stream before, during, and after test conditions were applied. Figure 39 shows the setup for the EFT testing. The results as shown in Figure 40 indicate slow and fast variations in temperature readings. The fast variations were mainly caused by applied EFTs. The slow variations were due to the fact that the LMT01 was measuring the ambient lab temperature, which is not very precisely controlled and kept on changing slowly by a few degrees. During the EFTs, the temperature error stayed well within 1ºC peak-to-peak (±0.5ºC) accuracy limits of the LMT01 as specified in the datasheet by using shielded twisted pair cable with a shield terminated to ground reference plane (GRP) at either end. However, as soon as the EFT test concluded, the fast variations fully disappeared and did not require any manual power reset.

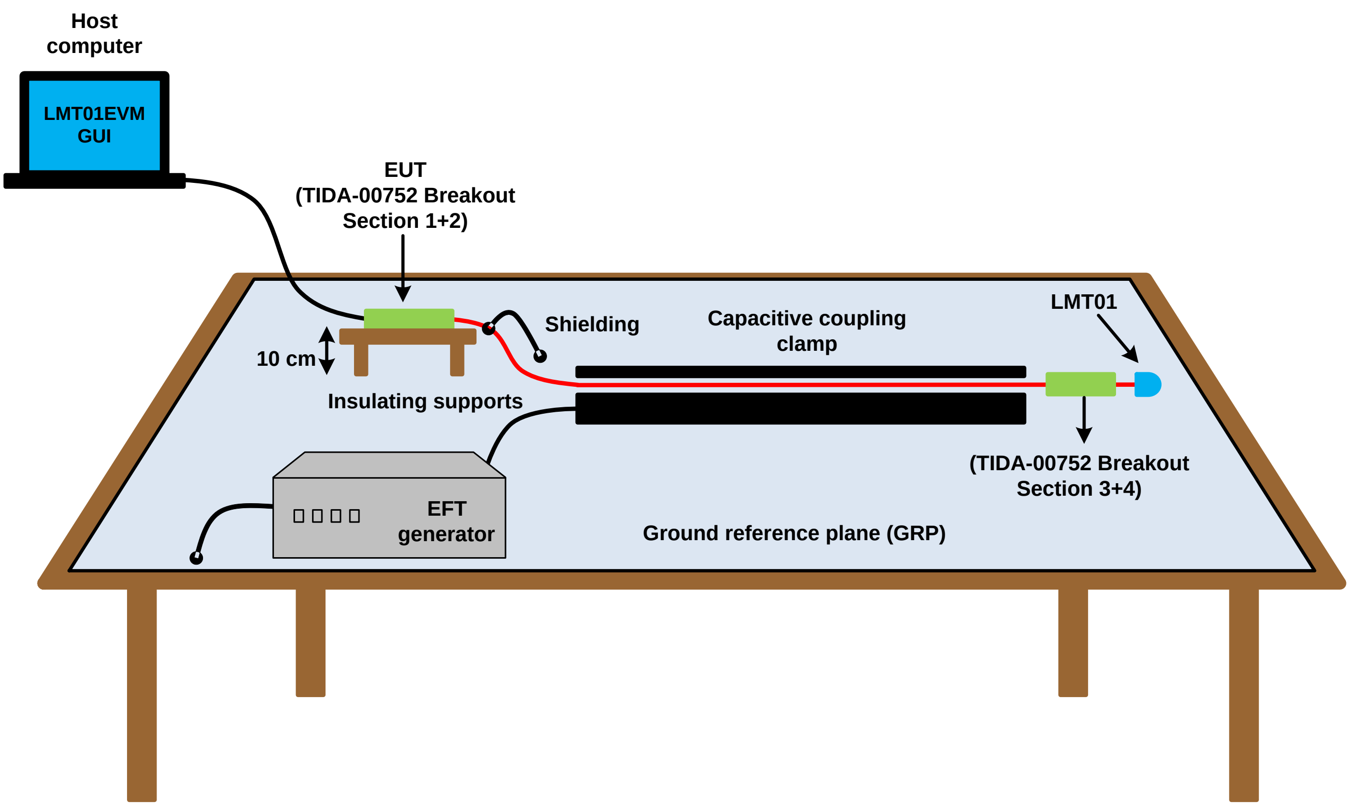

Figure 39. IEC61000-4-4 EFT Immunity Test Setup

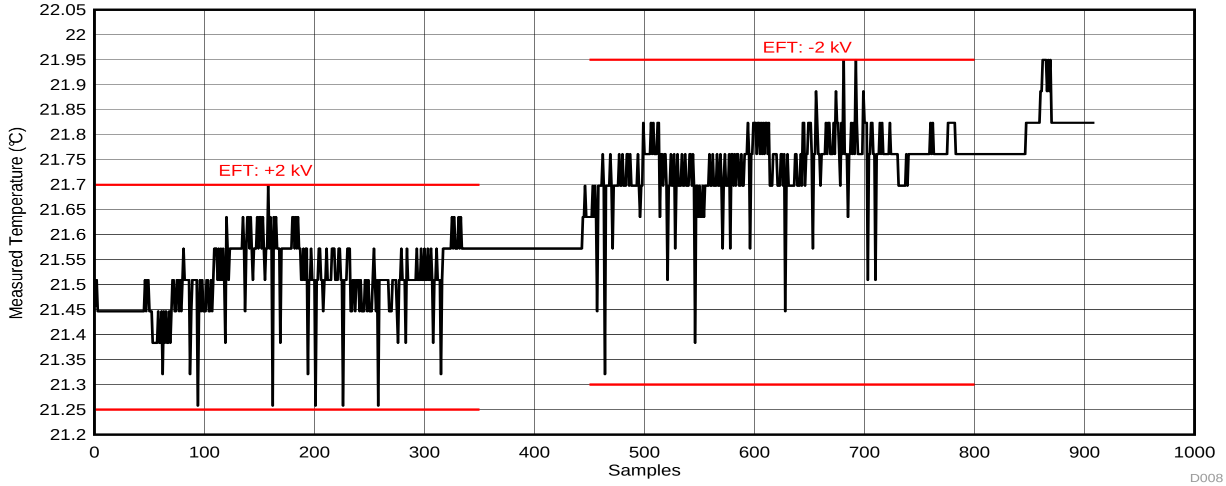

Figure 40. Performance During EFT Immunity Test Using Shielded Twisted Pair Cable

When using shielded cables, it is also necessary to determine how the shielding will be bonded otherwise the benefits are considerably reduced. To be effective, the shielding should be bonded over 360°. Figure 41 shows different ways of earthing the cable shielding. Use cable rounding clamp as shown in Figure 42 to improve bonding between the cable shield and GRP and off-course for better results.

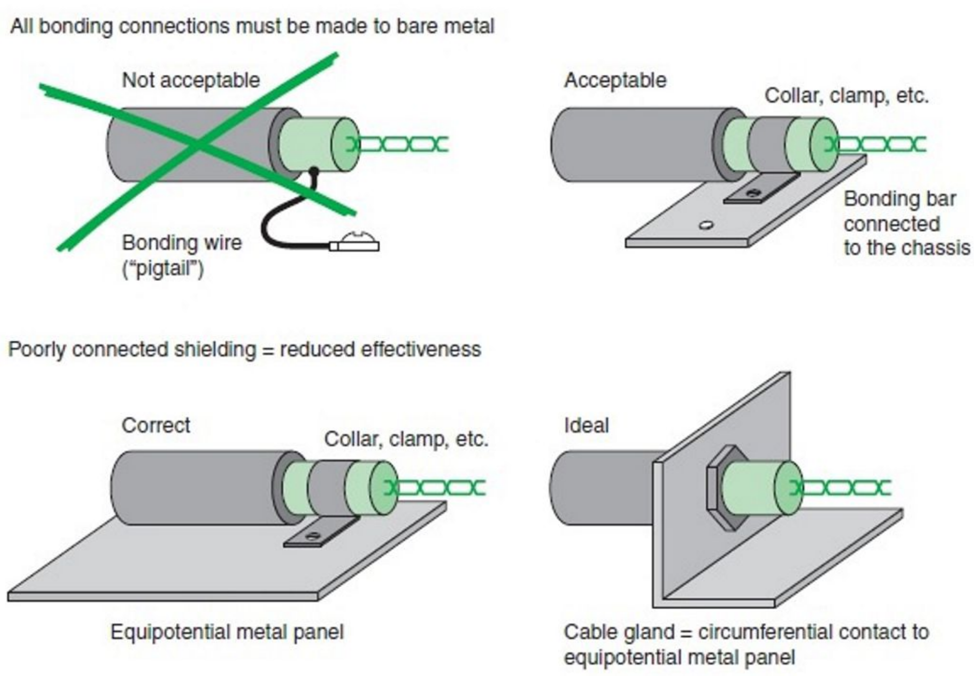

Figure 41. Implementations of Shielded Cables

Figure 42. Cable Grounding Clamp for Shielded Cables

Table 4. IEC61000-4-4 EFT Immunity Test Results

TEST CONDITION	PASS/FAIL CRITERIA	MEASURED PERFORMANCE	RESULTS
2-kV EFT	Temperature error < 1ºC peak-to-peak (±0.5ºC)	< 0.45ºC peak-to-peak	Meets class-A
–2-kV EFT	Temperature error < 1ºC peak-to-peak (±0.5ºC)	< 0.65ºC peak-to-peak	Meets class-A

7 Design Files

7.1 Schematics

To download the schematics, see the design files at TIDA-00752.

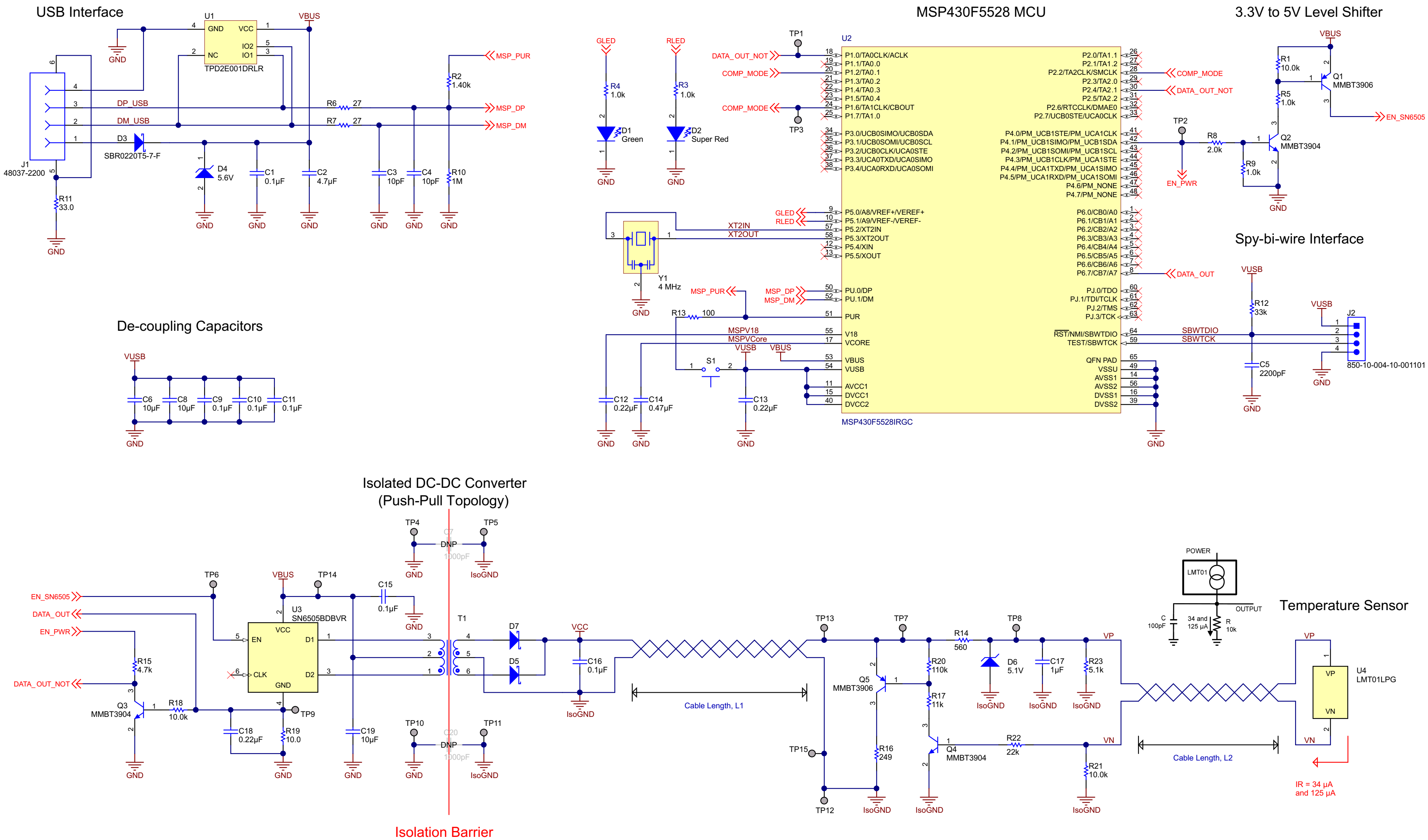

Figure 43. TIDA-00752 Schematics

7.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00752.

7.3 Layout Prints

To download the layout prints, see the design files at TIDA-00752.

7.4 Altium Project

To download the Altium project files, see the design files at TIDA-00752.

7.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00752.

7.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00752.

8 References

1. Texas Instruments, *LMT01 0.5°C Accurate 2-Pin Digital Output Temperature Sensor with Pulse Count Interface*, LMT01 Datasheet (SNIS189)
2. Texas Instruments, *SN6505 Low-Noise 1-A Transformer Drivers for Isolated Power Supplies*, SN6505 Datasheet (SLLSEP9)
3. Texas Instruments, *Mixed-Signal Microcontrollers*, MSP430F5528 Datasheet (SLAS590)
4. Texas Instruments, *TPD2E001 Low-Capacitance 2-Channel ESD-Protection for High-Speed Data Interfaces*, TPD2E001 Datasheet (SLLS684)
5. Texas Instruments, *LMT01EVM User's Guide* (SNIU027)

9 About the Authors

SHARAD YADAV is a Systems Engineer at Texas Instruments India where he is responsible for developing reference design solutions for the industrial segment. Sharad has eight years of experience in high-speed digital, mixed-signal boards, low-noise analog, and EMC protection circuit design.

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Revision B History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from A Revision (March 2016) to B Revision	Page
• Deleted Room Monitors, Appliances, and Power Supplies and Battery Thermal Management from Featured Applications	1

Revision A History

Changes from Original (December 2015) to A Revision	Page
• Changed from preview page	1