TI Designs: TIDA-00811
Accurate Temperature, Light Sensing, and Diagnostics Reference Design for Smart Grid Applications

TEXAS INSTRUMENTS

Description

This reference design provides accurate measurements of ambient light intensity used to detect arc flash faults with a fast response of 1 ms, minimizing damages to power distribution switchgear. This design also monitors temperature (using switch, analog, digital, or remote), humidity, dust, and pressure accurately for online monitoring of busbar, transformers, and capacitor banks for early indication of insulation failures, or ageing, resulting in increased operational life. This design provides a unique quick diagnostics approach for diagnostics of an ambient light sensor (ALS), increasing the system reliability. The sensors can be interfaced to microcontrollers with I^{2}C or a low-power, wireless interface to perform weather transmitter functions for continuous online monitoring.

Resources

|	
TIDA-00811	Design Folder
ADC101C021	Product Folder
OPA320	Product Folder
OPT101	Product Folder
PCA9515A	Product Folder
TMP102	Product Folder
HDC1080	Product Folder
TMP107	Product Folder
TMP175	Product Folder
LM35	Product Folder
DAC101C081	Product Folder
TMP302	Product Folder
TPL0401A-10	Product Folder
OPT3001	Product Folder
SN74LVC1G125	Product Folder
TS5A3157	Product Folder
OPT3006	Product Folder
SN74LVC2G32	Product Folder
SN74LVC1G3157	Product Folder
MSP430FR5729	Product Folder

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Features

- Measures Light, Temperature, Humidity, Dust, Vibration and Pressure With Support for Multiple Types of Temperature and Ambient light Sensors
- Measures Arc Flash Light Using Analog Output ALS for Fast Response of < 1 ms
- Uses 10-Bit SAR ADC to Measure Output of ALS With I^{2}C Interface and Alert Output for Measuring ALS Output
- Uses Hardware Comparator for Fast Fault Response to Ambient Light Changes, Threshold Can Be Set Using 10-Bit DAC or Digital Potentiometer
- Measures Onboard Ambient Temperature Using Analog or Digital Output Temperature Sensor With High Accuracy of ±1°C
- Measures Remote Temperature Using Daisy-Chain UART Interface, Alert Output, and Capability to Daisy Chain or Multiplex Sensors
- Supports Accurate Diagnostics of Ambient Light and Temperature Sensor With Diagnostics Time of ≈ 1 ms, Allowing On-Line Diagnostics
- Supports Multiple Sensors by Daisy Chaining or Using I^{2}C Interface With Unique Address
- Sensor Module Can Be Interfaced to Wired or Wireless MCUs Using CC1310, CC2650, CC2640, or MSP430FR5729 + CC2500
- Dual Bidirectional I^{2}C Bus Repeater Extends Bus Length Without Performance Degradation
- Digital Logic Based Fault Logic for MCU Wakeup
- Custom GUI for Interfacing and Performance Testing

Applications

- Multifunction Protection Relay
- Fault Indicator and Recloser
- Grid Automation
- RTU, FTU, DTU, or FRTU
- Substation Ethernet Switch

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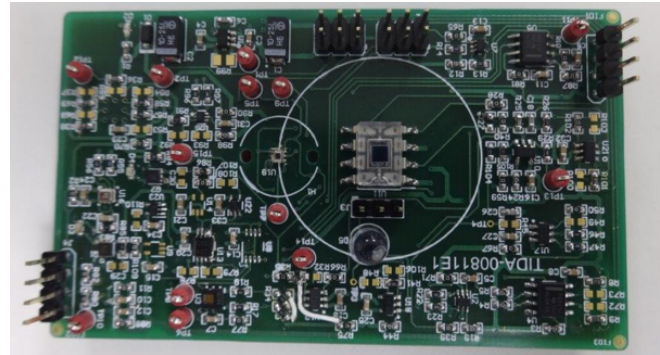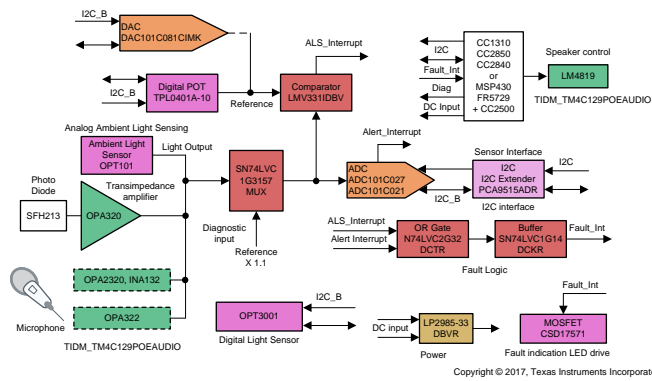
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1   System Description

Failing power systems is one of the common problems faced by power generation, transmission, and distribution companies. Some of the common causes of power failures include failures of critical assets including transformers, generators, breakers, and transmission lines. In low-voltage distribution, arc flash faults are one of the main causes of electrical systems failure.

In a substation, it is important to maintain the relative humidity level because when humidity is too low, it can contribute to ESD failures; when humidity is too high, it can cause water to condense, which causes electrical short circuits that trip circuit breakers and damages the equipment. High humidity and condensation can also cause equipment to rust and corrode, which ultimately leads to their failure.

Dust is everywhere, but is often invisible to the naked eye. Dust consists of fine particles in the air that originates from various sources such as soil, dust lifted by weather, and pollution. Dust in an electrical system installation may contain small amounts of textile, paper fiber, and minerals from outdoor soil. Dust may also include natural contaminants, such as chlorine from the marine environment and industrial contaminants such as sulfur. The accumulation of dust and debris on electronic equipment increases the working temperature of the equipment and reduces the reliability and working life of the equipment in accordance to the Arrhenius effect. As a result, the reliability of equipment decreases with an increase in the operating temperature. The moisture and corrosive elements that are present in the dust can cause premature board failure due to the corrosion of the electronic or mechanical components.

This reference design provides approach for sensing High intensity ARC flash light accurately including diagnostics that helps identify ARC flash faults fast, reliable and accurately protecting expensive switchgear from damages due to ARC flash faults. This design also provides solution to monitoring of temperature, (On-board or remote, digital or analog), humidity, pressure used for condition monitoring of power transformers, capacitor banks and other power system high voltage equipments to identify ageing, failures and provide early indication for the purpose of preventive maintenance. The measurement of Light, Temperature and Humidity also provides solutions for monitoring partial discharge in Power systems High voltage equipments preventing expensive and abrupt failures. Integration of Multiple types of temperature sensors provides options for customers to easily evaluate and choose the required sensor based on accuracy and interface. This TI design reduces the efforts of choosing, integrating and testing for grid applications reducing design cycle . The temperature sensor approaches of this design can be integrated with Fault indicator, Automatic Recloser, Protection relay Processor module , AC analog input module or other grid end equipments for continuous monitoring, temperature compensation and protection during over temperature reducing system failures resulting in increased equipment operational life.

This design showcases use of Alert function provided by ADC and other sensors to reduce the MCU power consumption. The Alert output can also be used for quick identification of the faults by setting the threshold and connecting the output to MCU interrupt inputs

Temperature sensor TMP107 with option to daisy chain up to 32 devices and communication using single wire provides flexibility in measuring transformer winding temperature or multiple capacitor bank temperature in a panel. The extended temperature measurement range provides flexibility to use the sensor inside power distribution panels with high ambient temperature up to 85°C

1.1 Featured Applications

This section provides information on the different end equipment applications that can use this reference design.

1.1.1 Multifunction Protection Relay

A multifunction protection relay consists of multiple modules and are connected inside the panel and near generators and transformers. Exposure to humidity, temperature, vibration, and dust can significantly reduce the operating life and characteristics. One can estimate the operational life of the system by monitoring temperature and humidity.

1.1.2 Grid Automation Including Terminal Units and Ethernet Switches

Arc flash protection is provided in distribution automation systems to monitor BUSBAR and switchgear against arc flash faults. Contactless temperature sensing monitors BUSBAR and switchgear temperature continuously. Weather sensor monitors the substation weather to indicate the environment conditions of the substation including the equipments in the substation. Humidity, temperature, and pressure data are used for forecasting the weather to predict demand. Remote terminal units monitor substations remotely and provide the weather data to a central monitoring system in real time to indicate the environment conditions of the remote substation. In multiport Ethernet, the form factor is critical and makes the enclosure design and thermal management a challenge. Sensing the internal Ethernet switch temperature is critical to the system performance and reliability.

1.1.3 Thermal Monitoring and Environment Analysis of Switchgear Assets

All objects above zero kelvin (–273.15°C, –459°F) radiate energy proportional to their temperature. This relationship is defined by the Stefan-Boltzmann Law. An infrared temperature sensor, or pyrometer, absorbs the radiated energy to measure it. A visible or thermal image, combined with contactless temperature measurement, is used to monitor substation power transformers, power cables, circuit breakers, and intrusion. The TMP00x devices contain a thermopile, which absorbs this energy and reports a corresponding voltage in the sensor voltage register 0x00.

This reference design can be used to measure electric temperature in subsystems, including thermography. Thermal monitoring of low- or mid-voltage switchgear and conditioning monitoring of circuit breakers or vacuum contactors play an important role in ensuring power systems reliability, resulting in saving of energy and maintenance cost to utilities. Non-contact infrared temperature sensors measure the surface temperature of an object (transformer, motor, or switchgear) to identify a hot spot from a safe distance. Continuous temperature measurement prevents equipment failures and unscheduled down time. Utilities use contactless temperature sensing to monitor switchgear panels, power transformers, circuit breakers, vacuum contactors, back-up batteries, electric motors, motor bearings, and other equipments on the substation bay.

1.1.4 Overhead Fault Indicator and Autorecloser Control

Overhead fault indicators and reclosers are mounted outdoor on the poles in extreme conditions in mid-voltage distribution automation. The systems are protected against overtemperature and monitor the weather conditions for internal diagnostics. An anti-condensation heater is provided in the recloser control unit (load current reduces condensation inside the recloser unit) for internal humidity control and is based on temperature and humidity.

1.2 Key System Specifications

The key system specifications are featured in the following subsections.

1.2.1 ALS Specifications

Table 1 provides the key system specifications for the ALS.

Table 1. Key System Specifications of ALS

SERIAL NUMBER	PARAMETERS	DESCRIPTION	COMMENTS
1	Integrated light sensor	Integrated ALS with analog output	1 ms or less response time
2	External light sensor	ALS with external trans-impedance amplifier	≥ 10-µs response time
3	Light intensity measurement	ADC for measuring light intensity	10-bit I^2C interface
4	Digital light sensor	ALS with digital output	100-ms response time
5	Diagnostics	DAC and digital potentiometer	10-bit, 10K, 256 steps, I^2C
6	Fast fault detection	Comparator based	10 µs or less response time
7	Fault indication	Alert output and buffered fault output with digital logic	With settable threshold
8	Sensor interface	Interrupt output and I^2C interface	—

1.2.2 Temperature and Humidity Sensor Specifications

Table 2 provides the key system specifications for the temperature and humidity sensor module.

Table 2. Key System Specifications of Temperature Sensor

SERIAL NUMBER	PARAMETERS	DESCRIPTION	COMMENTS
1	Onboard local	Temperature switch	Pin selectable, trip-point accuracy: ±0.2°C, window comparator
2	Onboard local	Analog output	Linear + 10-mV per °C , 0.5°C ensured accuracy (at 25°C)
3	Onboard local	Digital output	I^2C interface, ±2°C or less accuracy
4	Contact, remote	Digital output, daisy chaining	Multiplexed, UART interface
5	Humidity	Digital output	Relative humidity accuracy ±2%
6	Fault indication	Alert and buffered fault output with digital logic	With settable threshold
7	Diagnostics	Humidity and temperature	Heater for temperature and humidity
8	Interface	Interrupt output and I^2C interface	—

2 System Overview

This reference design consists of multiple options to measure ambient light and temperature accurately. Additionally, this reference design allows for sensing dust, acoustic input, and pressure by leveraging other reference designs.
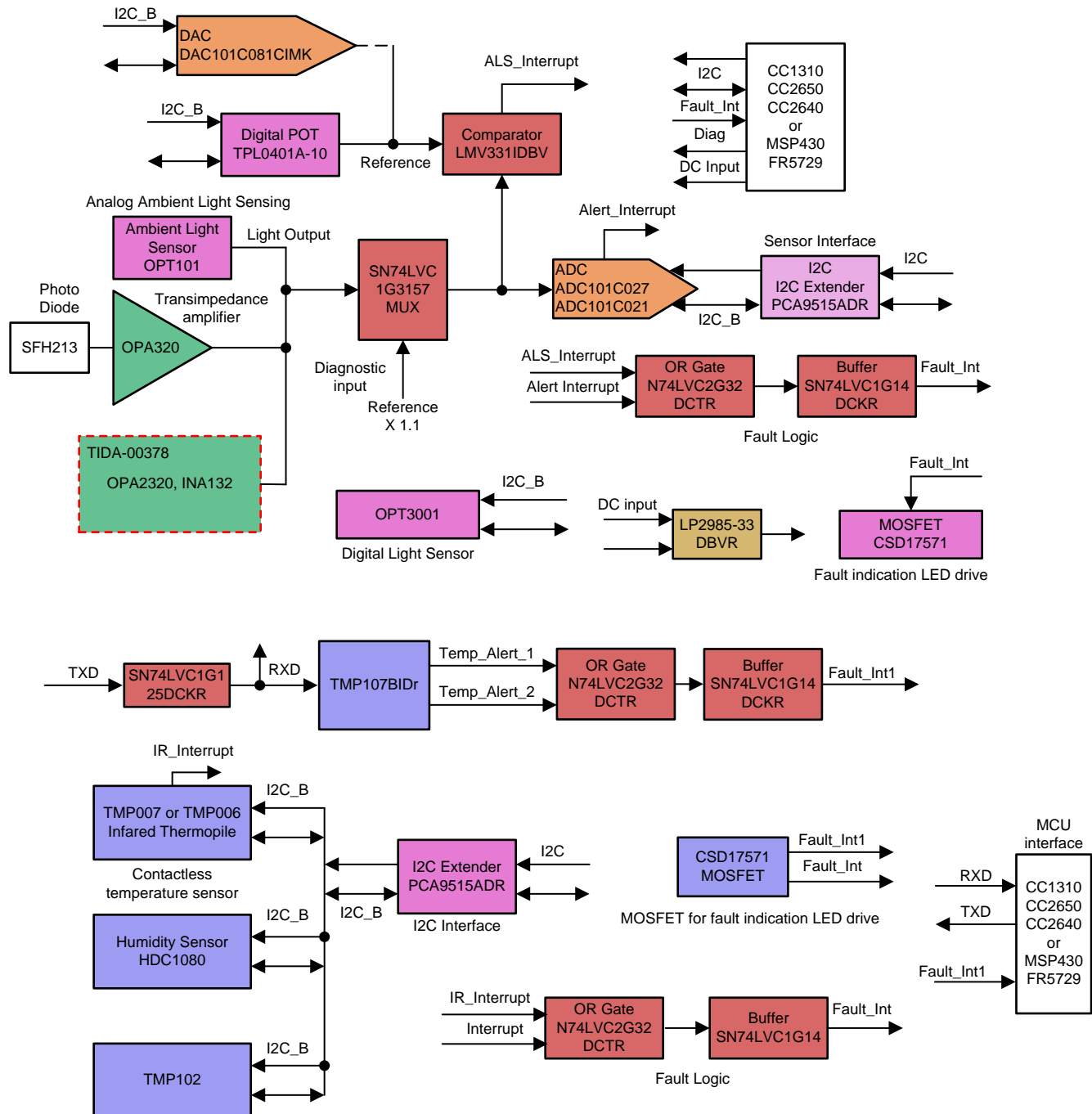
2.1 Block Diagram

This reference design for ambient light and environment monitoring has the following functional blocks:
- High-intensity arc flash or ambient light sensing with onboard sensors and fault interrupt
- Compact temperature sensing module: Local, remote, or contactless with ambient light sensing

2.1.1 ALS (Including High Intensity Arc Flash)

Figure 1 features the following subsystems:
- Light sensing with the OPT101 monolithic photodiode and single-supply transimpedance amplifier or OPA320 amplifier with an external photodiode for a faster response
- DAC101C081 or TPL0401A-10DCKR to generate reference voltage for the comparator output and diagnostics
- Digital logic-based fault detection and LED indication
- PCA9515ADR I²C buffer interface for extended range of communication and MSP430FR5729-based experimenter board for the host interface
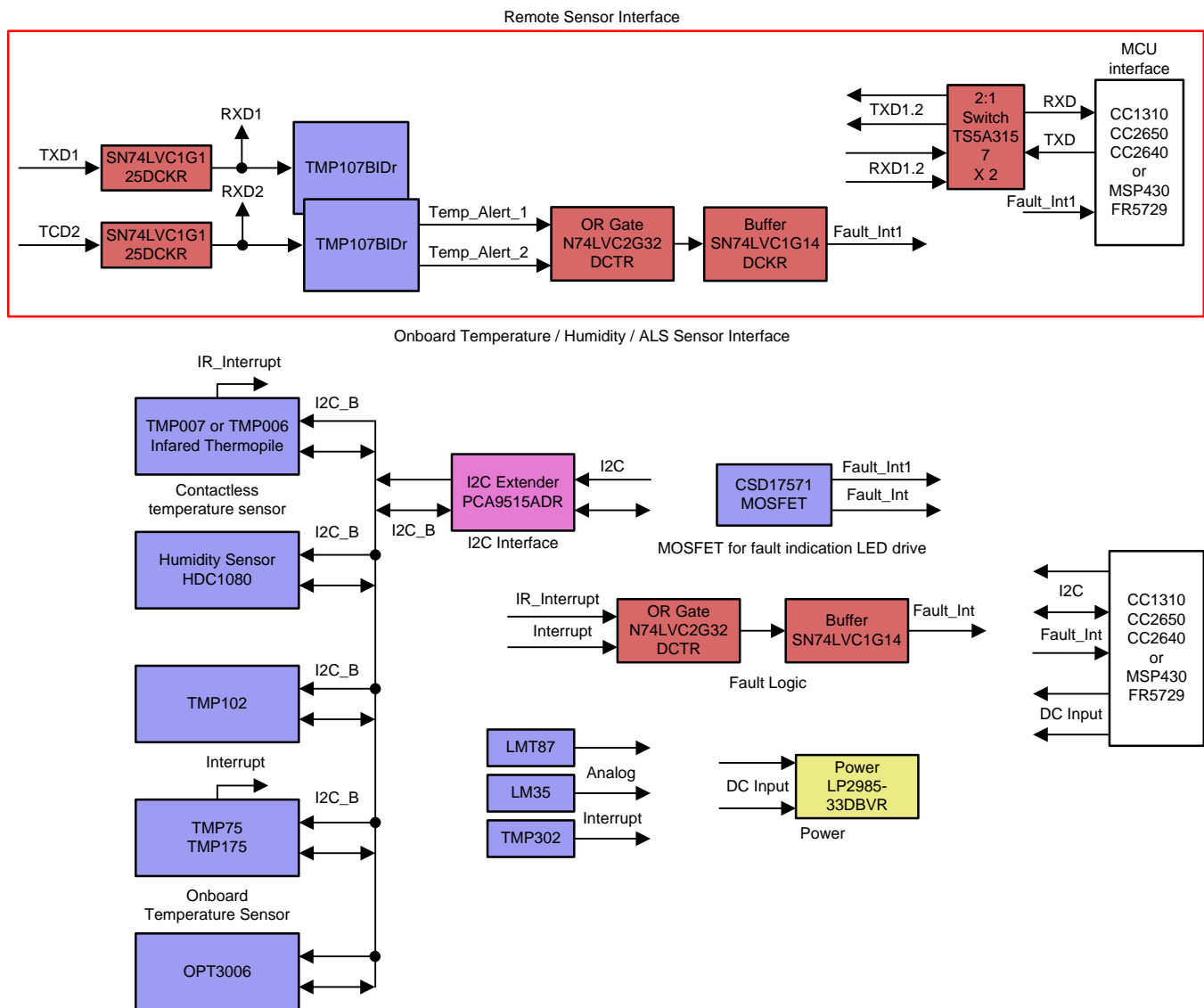
Figure 1. Block Diagram of ALS With Temperature Sensor

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2.1.2 Local or Remote Temperature Sensing

Figure 2 features the following subsystems:

- Onboard temperature sensor TMP175 with an I^{2}C interface and a measurement accuracy of ±2°C (maximum) from −40°C to 125°C, programmable resolution, and fault queue
- Onboard temperature sensor TMP102 with an I^{2}C interface and measurement accuracy without calibration: 2.0°C (max) from −25°C to 85°C
- Onboard temperature sensor LM35 (±0.5°C) with analog output
- Onboard temperature switch TMP302 with pin-selectable trip point
- TMP107 ±0.4°C temperature sensor with daisy-chain UART, EEPROM, and alert function
- PCA9515ADR I^{2}C buffer interface for an extended range of communication and MSP430FR5729-based experimenter board for a host interface

Remote Sensor Interface

Onboard Temperature / Humidity / ALS Sensor Interface

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Figure 2. Block Diagram of Local, Remote, or Contactless Temperature Sensing

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2.2 Design Considerations

2.2.1 Microcontroller

The microcontroller (MCU) used to interface with the sensor is the MSP430FR5729. The MSP430™ MCU interfaces to the sensors through GPIO and I^{2}C interface through the PCA9515. Depending on the application, the MSP432P401R or wireless MCUs CC1310, CC2640, or CC2650 can be interfaced.

2.2.2 Light Intensity Measurement and Level Sensing

This section details the different approaches to light intensity measurement and level detection.

2.2.2.1 Ambient Light Sensing (Light to Analog Output)

The arc flash subsystem senses light using the integrated sensor OPT101 or SFH213 photodiode with a transimpedance amplifier. The output is analog and has a faster response. In applications requiring a response time of >100 ms and a digital interface, the OPT3001 or OPT3002 can be used. When smaller form factor is required, consider the OPT3006.

2.2.2.2 Light Intensity Analog Output Measurement

The analog output of the OPT101 or transimpedance amplifier is interfaced to the ADC101C021 or ADC101C027.

2.2.2.3 Light Intensity Level Indication

In applications requiring to detect the light intensity with a fast response, the DAC101C081C or digital potentiometer TPL0401A-10 can be used to set the threshold, and the comparator LMV331 can be used to detect the level. This device can be used to capture pre- and post-data logging during a fault.

2.2.2.4 Light Intensity Level Detection Reference (Pickup Level)

The light sensor pick-up level can be adjusted by sensing the current intensity level and setting the comparator reference using the DAC101C081C or digital potentiometer TPL0401A-10.

2.2.3 Measuring Onboard (Local)Temperature and Humidity

This section details the different approaches to measure or indicate onboard temperature and humidity.

2.2.3.1 Temperature Switch

A temperature switch simplifies onboard temperature measurement and provides a digital output when the ambient temperature exceeds the set level. The TMP300 is a low-power, resistor-programmable, digital output temperature switch. The TMP302 offers low power (15 μA maximum) and ease of use through pin-selectable trip points and hysteresis. The TMP303 is a factory-programmed temperature window comparator.

2.2.3.2 Temperature Sensor With Analog Output

In cases where an MCU is used, an analog output temperature sensor can be used to measure local temperature. Depending on the accuracy requirement, the LMT87 or LM35 can be used.

2.2.3.3 Temperature Sensor With Digital Interface

In cases where the sensor board is connected away from the processor board, a temperature sensor based on the I^{2}C interface can be used. Multiple devices can be connected on the same bus, simplifying system design. Some of the common temperature sensors include the TMP102, TMP75, TMP175, or TMP275. Selecting the sensor depends on the accuracy requirement and interface addressing flexibility.

2.2.3.4 Humidity and Dust Sensor

Moisture content increases the risk of corrosion and overheating. Exposure to continuous humidity and dust results in corrosion of the primary equipment resulting in ageing. Humidity and temperature sensors are used to estimate life of these primary equipments. The humidity sensors HDC1080 or HDC1010 can be interfaced using I^2C. Particles or dust can be sensed using the OPA2320-based transimpedance amplifier, LED, and photo diode.

2.2.4 Remote Temperature Sensor

In applications where the temperature inside panels, capacitor banks, or winding are required to be measured, a remote temperature sensor with one wire interface can be used. The TMP107 with alert inputs and capability to daisy chain multiple devices have been used in this reference design. The multiplexing of the UART data is done using the SN74LVC1G125 and TS5A3157DCKR. The TMP423 can be used to measure multiple remote sensor inputs accurately.

2.2.5 Contactless Temperature Sensor

In applications that need to measure the temperature of the BUSBAR or panel, contactless temperature sensors are used. The TMP007 with a built-in math function or TMP006 can be used.

2.2.6 Fault Indication Logic, Self-Diagnostics, and Power

The fault indication logic to sense light intensity, overtemperature, or humidity is generated using digital logic. The SN74LVC2G32, SN74LVC1G14, SN74LVC1G17, and CSD17571 are used to sense, communicate over long distances, and indicate the faults onboard. Provision for self-diagnostics of light intensity input is provided using the SN74LVC1G3157. The required power is generated using the LP2985-33 LDO. The diagnostics loop is accomplished in < 1 ms to avoid missing arc flash faults by making use of the analog-to-digital converter (ADC) alert output and fast fault detection comparator.

2.2.7 Pressure Sensor

The pressure change that occurs during arc flash fault is measured by the BMP280. The BMP280 is an absolute barometric pressure sensor especially designed for mobile applications. The sensor module is housed in an extremely compact package and interface using I^2C.

2.2.8 Arc Flash Faults and Causes

An arc fault is the most devastating type of fault in low- and mid-voltage switchgear. If an arc fault occurs, the arc flash system reduces arc energy by quickly clearing the current feeding the arc. Technology for arc flash detection (AFD) significantly decreases the time it takes a relay to trip in response to an arc fault, which reduces hazardous arc flash incident energy. AFD systems combine light-sensing technology with fast overcurrent protection to provide high-speed AFD. Combining these technologies allows high-speed tripping during arc flash events without over tripping for external faults.

The light sensor protects against a false trip for an external fault. A protective relay with overcurrent can sense the current surge from an arc-flash event, but it cannot know whether it was an internal or external fault on the feeder or the protected equipment downstream. Internal and external faults inside the switchgear can be differentiated by sensing the light flash using light sensors. AFD-equipped protective relays detect an arc-flash event by detecting the simultaneous occurrence of both the fault current and the arc flash light, triggering an immediate trip within the first quarter cycle of the arc flash event. Arcing faults are typically caused by human errors, resulting in equipment failures, or aging equipment failing to operate according to specification. Some more common equipment failures are connections in the switchgear power cable and circuit breaker racking mechanisms.

Some operational environments animals such as rodents and snakes are known to cause arc faults when entering or nesting electrical equipment. Short circuits caused by arcing can be very destructive to switchgear equipment and dangerous to humans as well. Arcing faults release large amounts of energy in the form of radiant heat, intense light, and high pressure waves. The rapid increase of temperature expands the volume of the air, causing a pressure wave, which in turn leads further to a potentially damaging sound wave as well. The extreme temperatures cause switchgear components to vaporize within milliseconds. High pressure leads to opening of switchgear doors, releasing extreme energy to exposed personnel should they be in the area during the arcing fault. In addition to direct light, temperature and pressure affect other danger factors include release of toxic gases and burning shrapnel.

2.2.8.1 Arc Flash Solutions and Point Sensor

Common solutions for AFD solutions include current measurement, point sensors, or loop sensors for arc flash light sensing, particle sensing, acoustic sensing, vibration sensing, and pressure sensing. The advantages of point sensors are ease of installation for new and retrofit installations and can indicate the exact fault location as sensors are installed in each protected compartment. If there are large components such as circuit breakers that cast shadows over wider areas, more than one point sensor is required. Arc light point sensors are typically installed in metal clad compartments, providing quick accurate location of the faulted area. Arc flash fiber loop sensors are installed typically to cover a wider protected area with one fiber when no need for more exact fault location exists. The following approaches can be considered for ambient light sensing, including the integrated light sensor OPT101, photodiode interfaced to the transimpedance amplifier OPA320, or the ALS TEMT6200FX01.

2.2.8.2 System Requirements

Some of the critical requirements for the design of system for arc flash fault sensing include:

*   Measuring wide input current
*   High-intensity light during an arc flash
*   Adjusting light sensor pickup dynamically
*   Determining the arc flash fault
*   Providing trip signal to breaker within 2 ms
*   Wired (copper or fiber) or wireless communication to indicate the status of the equipment being protected
*   Interfacing to a point or loop sensor placed remotely

2.2.8.3 Sensor Pickup Level Adjustment

The pickup level of the arc flash fault of the light sensors is set as a percent of full scale (100 percent). If there is change is ambient light, the pickup level has to be adjusted. The pickup level can be adjusted dynamically or statically. Capability to adjust the pickup level dynamically improves detection accuracy and reduces unwanted false trips.

2.2.9 Critical Asset Condition Monitoring and Causes

The quality of a electricity supply is measured in terms of the frequency and duration of interruptions. Interrupting supplies results in huge financial losses as well as utilities and must be minimized as much as possible. Failure of power system equipment is responsible for a large proportion of power system outages and interruption of supply. Other causes of interruption include extreme weather conditions, partial discharge, temperature rise, dust, and humidity among others. If failures can be predicted before they occur, action can be taken to reduce the occurrence of unplanned outages of equipment thus contributing to meeting performance targets and reducing the cost of interruptions.

2.2.9.1 Solutions

Condition monitoring of critical power system components such as transformers, circuit breakers, and power lines is essential. This becomes very necessary as the components age or get into the wear out period. Some of the commonly monitored equipments include transformers, circuit breakers, transmission lines, and power cables.

2.2.9.2   System Requirements for Conditioning Monitoring

Some of the common requirements for conditioning monitoring include:
- Temperature measurement: Local, remote, or contactless (infrared)
- Humidity, dust, and dirt
- Vibration and partial discharge

2.2.9.3   System Requirements for Temperature Monitoring

Temperature measurement approaches for continuous monitoring include:
- Temperature switch
- Analog temperature sensor
- Digital temperature sensor
- Humidity sensor with temperature
- Remote temperature sensing with an option to daisy chain multiple devices
- Contactless temperature measurement

2.2.9.4   System Interface

Consider the following interfaces:
- Buffered interrupt output to indicate the fault
- Local MCU with a wired interface including I^2C or UART
- MCU with wireless interface for remote monitoring
- Fiber optic (FO) for communication in harsh environments

2.2.10   Reference Design Advantages

This section details the advantages provided by this reference design.

2.2.10.1   Arc Flash Fault Sensing

This reference design showcases the following approach to light sensing:
- Sensing light using different ALS's, including an integrated light sensor for a 1-ms response time or an external photo diode with a transimpedance amplifier for a faster response, and a digital light sensor for weather monitoring
- ADC with an alert output to measure light intensity
- Hardware comparator for fast sensing of light level for triggering event data logging
- Diagnostics using DAC or potentiometer to set the reference
- Interface to MCU for fault capture and analysis, including a buffered interrupt output for quick fault identification, I^2C interface for reading the sensor outputs and setting the light levels, a UART interface for remote temperature sensors (with an option to expand the interface including wireless or FO)

2.2.10.2   Temperature Sensing

This reference design showcases the following approaches to temperature sensing:
- Sensing of temperature using a temperature switch reduces MCU processing time
- High-accuracy analog temperature sensor interfaced to a 10-bit ADC
- High-accuracy digital temperature sensing with a I^2C interface
- High-accuracy remote digital temperature sensing with a UART interface
- Contactless temperature sensing using thermopile sensors with math function
- Humidity and temperature sensor for environment monitoring

2.3 Highlighted Products—System Design

This section describes the TI products used in this reference design with design calculations.

2.3.1 MCU and I²C Interface

2.3.1.1 MSP430FR5729

The TI MSP430FR572x family of ultra-low-power MCUs consists of multiple devices that feature embedded FRAM nonvolatile memory, an ultra-low-power 16-bit MSP430 CPU, and different peripherals targeted for various applications. FRAM is a new nonvolatile memory that combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash, all at lower total power consumption. Peripherals include a 10-bit ADC, a 16-channel comparator with voltage reference generation and hysteresis capabilities, three enhanced serial channels capable of I²C, SPI, or UART protocols, an internal DMA, a hardware multiplier, an RTC, five 16-bit timers, and digital I/Os (see the MSP430FR5729 product page).

2.3.1.2 PCA9515 I²C Buffer

This dual bidirectional I²C buffer is operational at 2.3- to 3.6-V VCC. The device contains two identical bidirectional open-drain buffer circuits that enable I²C and similar bus systems to be extended without degradation of system performance. The PCA9515A buffers both the serial data (SDA) and serial clock (SCL) signals on the I²C bus, while retaining all the operating modes and features of the I²C system. This enables two buses of 400-pF bus capacitance to be connected in an I²C application. Using the PCA9515A enables the system designer to isolate two halves of a bus, accommodating more I²C devices or longer trace lengths (see the PCA9515A product page).

2.3.2 Light Intensity Measurement

Figure 3 shows the different approaches used to sense ambient light.
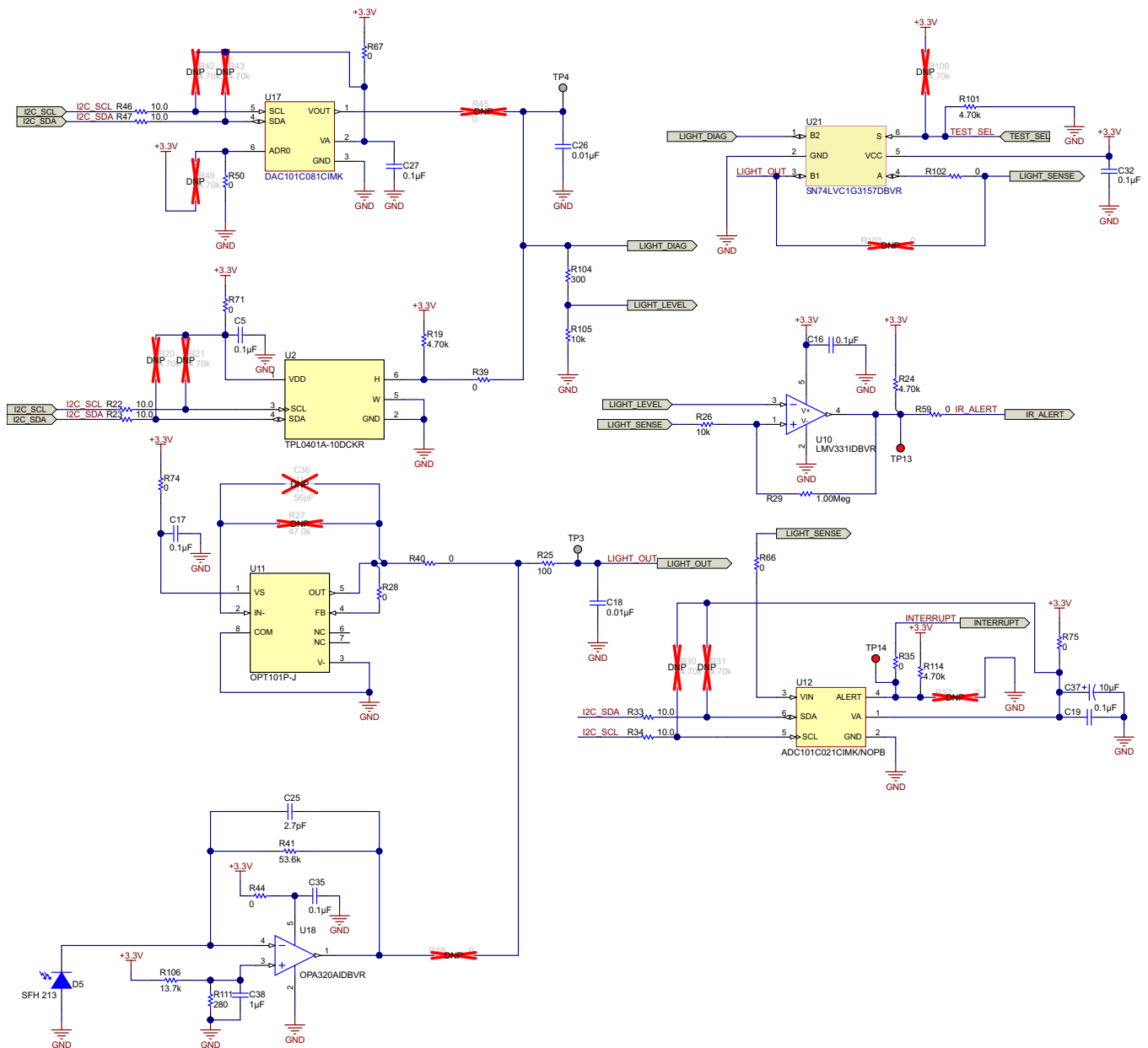
Figure 3. Light Intensity Measurement Subsystem Schematic

2.3.2.1 Ambient Light Sensing

2.3.2.1.1 OPT101 Photodiode With On-Chip Transimpedance Amplifier

The OPT101 is a monolithic photodiode with an on-chip transimpedance amplifier. The integrated combination of a photodiode and transimpedance amplifier on a single chip eliminates the problems commonly encountered in discrete designs, such as leakage current errors, noise pick-up, and gain peaking as a result of stray capacitance. Output voltage increases linearly with light intensity. The amplifier is designed for single or dual power-supply operation. The photodiode operates in the photoconductive mode for excellent linearity and low dark current. See Section 8.3.2.1: Changing Responsivity of the OPT101 datasheet for more information (see the OPT101 product page).

2.3.2.1.2 *OPA320 Configured as Transimpedance Amplifier*

The OPA320 (single channel) is a new generation of precision, low-voltage CMOS operational amplifiers optimized for very low noise and wide bandwidth while operating on a low quiescent current of only 1.45 mA (see the OPA320 product page).

2.3.2.1.3 *OPT3001, OPT3002, or OPT3006 Digital Light Sensor*

The OPT3001 is a sensor that measures the intensity of visible light. The spectral response of the sensor tightly matches the photopic response of the human eye and includes significant infrared rejection. The OPT3001 is a single-chip lux meter, measuring the intensity of light as visible by the human eye. The precision spectral response and strong IR rejection enables OPT3001 to accurately meter the intensity of light as seen by the human eye regardless of light source. Measurements can be made from 0.01 lux up to 83k lux without manually selecting full-scale ranges by using the built-in, full-scale setting feature. This capability allows light measurement over a 23-bit effective dynamic range (see the OPT3001 product page).

2.3.2.2 *Measuring Light Intensity Using 10-Bit SAR ADC ADC101C021*

The ADC101C021 is a low-power, 10-bit ADC that operates from a 2.7- to 5.5-V supply. The converter is based on an SAR architecture with an internal track-and-hold circuit that can handle input frequencies up to 11 MHz. The ADC101C021 operates from a single supply, which also serves as the reference. The device features an I²C-compatible serial interface that operates in all three speed modes, including high-speed mode (3.4 MHz). The alert feature of the ADC provides an interrupt that is activated when the analog input violates a programmable upper or lower limit value. The device features an automatic conversion mode, which frees up the controller and I²C interface. In this mode, the ADC continuously monitors the analog input for an "out-of-range" condition and provides an interrupt if the measured voltage goes out of range. The ADC101C021 and ADC101C027 are part of a family of pin-compatible ADCs that also provide 12- and 8-bit resolution. For 12-bit ADCs, see the ADC121C021 and ADC121C027. For 8-bit ADCs, see the ADC081C021 and ADC081C027 (see the ADC101C021 product page).

2.3.2.3 *Detecting Light Intensity Level*

2.3.2.3.1 *Light Level Detection Reference Output Using DAC101C081C or Digital Potentiometer TPL0401A-10*

The DAC101C081 device is a 10-bit, single-channel, voltage-output digital-to-analog converter (DAC) that operates from a 2.7- to 5.5-V supply. The output amplifier allows rail-to-rail output swing and has an 6-µs settling time. The DAC101C081 uses the supply voltage as the reference to provide the widest dynamic output range and typically consumes 132 µA while operating at 5.0 V. The DAC101C081 use a two-wire, I²C-compatible serial interface that operates in all three speed modes, including high-speed mode (3.4 MHz). The DAC has an output slew rate of 1 V/µs and an output voltage settling time of < 6 µs. The TPL0401x-10 device is a single-channel, linear-taper digital potentiometer with 128 wiper positions. The TPL0401x-10 has the low terminal internal and connected to GND. The position of the wiper can be adjusted using an I²C interface. The part has a 10-kΩ end-to-end resistance. The TPL0401x-10 has the low terminal internal and connected to GND. The wiper response time is < 5 µs (see the TPL0401A-10 and DAC101C081 product page).

2.3.2.3.2 *LMV331 Comparator*

The LMV331 is the single-comparator version. The LMV331 is the most cost-effective solutions for applications where low-voltage operation, low power, and space saving are the primary specifications in circuit design for portable consumer products (see the LMV331 product page).

2.3.3 Measuring Onboard Temperature and Humidity

This section details the onboard temperature and humidity sensors used in this reference designs.

2.3.3.1 Temperature Sensor With Digital Interface

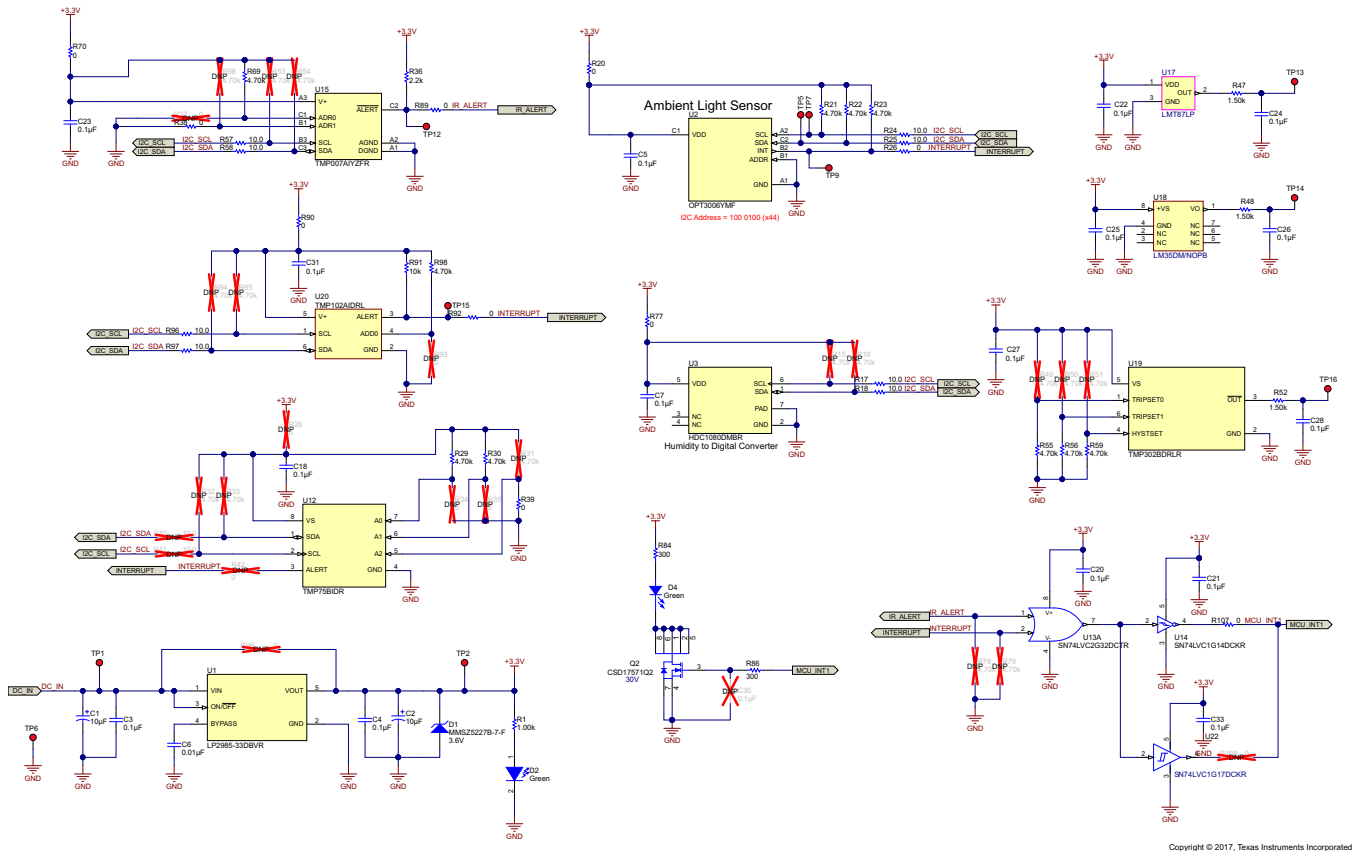The following subsections detail the different temperature sensors used in this reference design.

Figure 4. Temperature Sensor With Digital Interface Schematic

2.3.3.1.1 TMP102 Local Onboard Temperature Sensor

The TMP102 device is a digital temperature sensor ideal to replace NTC and PTC thermistors where high accuracy is required. The device offers an accuracy of ±0.5°C without requiring calibration or external component signal conditioning. These temperature sensors are highly linear and do not require complex calculations or look-up tables to derive the temperature. The on-chip 12-bit ADC offers resolutions down to 0.0625°C (see the TMP102 product page).

2.3.3.1.2 TMP75, TMP175, or TMP275 Accurate Local Onboard Temperature Sensor

The TMP75 and TMP175 devices are digital temperature sensors ideal to replace NTC and PTC thermistors. The devices offer a typical accuracy of ±1°C without requiring calibration or external component signal conditioning. These temperature sensors are highly linear and do not require complex calculations or look-up tables to derive the temperature. The on-chip 12-bit ADC offers resolutions down to 0.0625°C. The TMP175 and TMP75 both feature an SMBus Alert function (see the TMP75, TMP175, and TMP275 product page).

2.3.3.1.3 HDC1080 Onboard Humidity and Temperature Sensor

The HDC1080 is a digital humidity sensor with an integrated temperature sensor that provides excellent measurement accuracy at very low power. The HDC1080 operates over a wide supply range, and is a low-cost, low-power alternative to competitive solution in a wide range of common applications. The humidity and temperature sensors are factory calibrated (see the HDC1080 product page). Alternatively HDC2010 can be used based on the application requirement (see the HDC2010 product page)

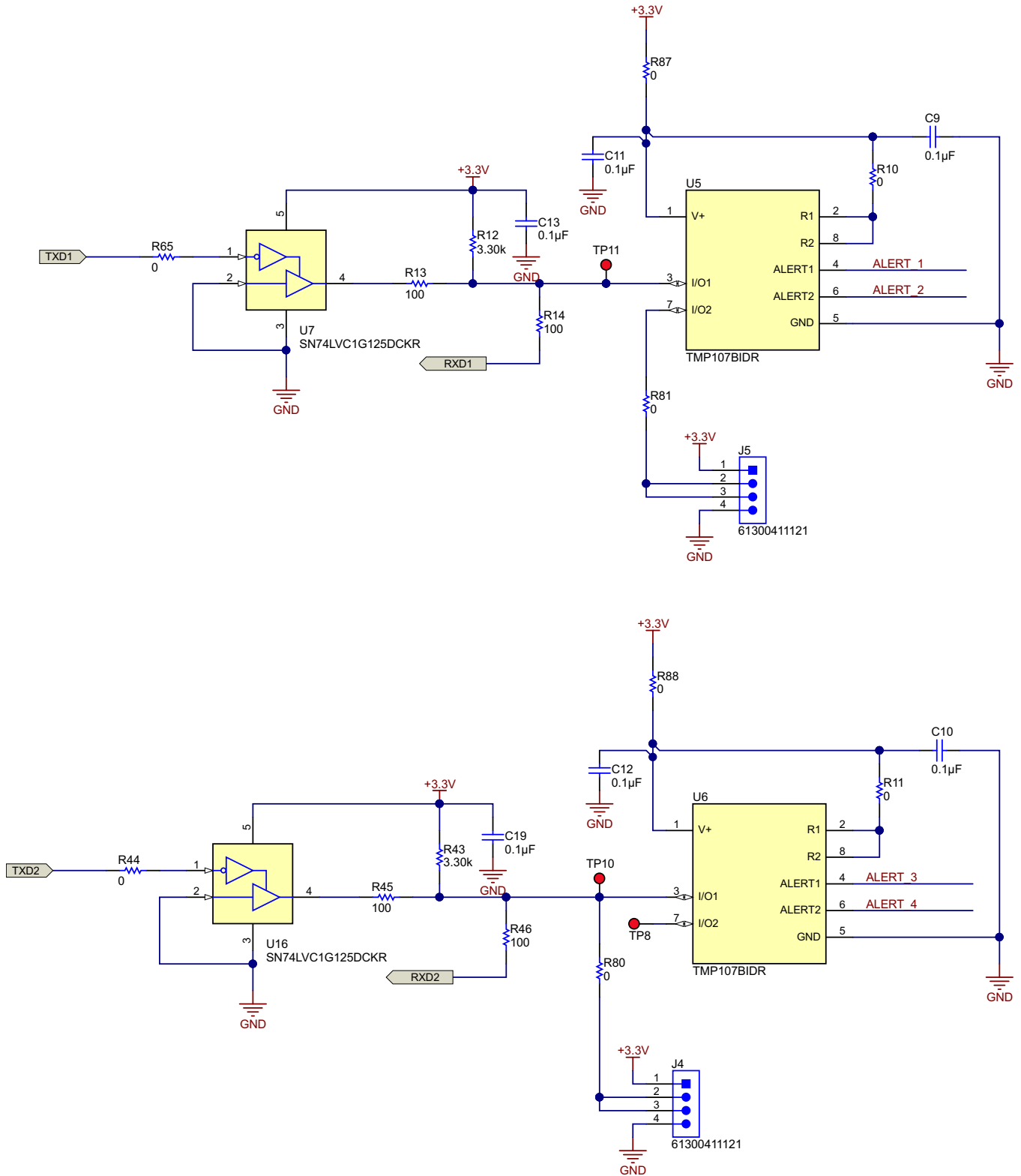### 2.3.3.2   *Temperature Sensor With Analog Output*

The LMT87 is a precision CMOS integrated-circuit temperature sensor with an analog output voltage that is linearly and inversely proportional to temperature. Its features make it suitable for many general temperature sensing applications. The LM35 series are precision integrated-circuit temperature devices with an output voltage linearly-proportional to the Centigrade temperature. The LM35 device has an advantage over linear temperature sensors calibrated in Kelvin because the user is not required to subtract a large constant voltage from the output to obtain convenient Centigrade scaling (see the LMT87 and LM35 product page).

2.3.3.3   *TMP300, TMP302, or TMP303 Temperature Switch*

The TMP300 is a low-power, resistor-programmable, digital output temperature switch. The TMP302 offers low power (15 μA maximum) and ease of use through pin-selectable trip points and hysteresis. The TMP303 is a temperature range monitor with low power (5 μA maximum) and a low supply voltage capability (as low as 1.4 V). These devices require no additional components for operation; they can function independent of microprocessors (MPUs) or MCUs (see the TMP300, TMP302, and TMP303 product pages).

2.3.4   Remote Temperature Sensor

This section details the subsystem design to measure remote temperature (see Figure 5).

Figure 5. Remote Temperature Sensor Schematics

2.3.4.1 Remote Temperature Sensor With TMP107

The TMP107 digital output temperature sensor supports a total of 32 daisy-chained devices. Each sensor has a unique 5-bit address stored in electrically-erasable programmable memory (EEPROM). The TMP107 is capable of reading temperatures with a resolution of 0.015625°C, and is accurate to within ±0.4°C in the range from –20°C to 70°C. The TMP107 is ideal for replacing NTC and PTC thermistors where high accuracy is required (see the TMP107 product page).

2.3.4.2 SN74LVC1G125 Three-State Line Driver for Remote Temperature Sensor

The SN74LVC1G125 device is a single-line driver with a three-state output. The output is disabled when the output-enable (OE) input is high. The CMOS device has high-output drive while maintaining low static power dissipation over a broad VCC operating range (see the SN74LVC1G125 product page).

2.3.4.3 TS5A3157DCKR Analog Switch for Interfacing Multiple Sensor Chain

The TS5A3157 device is a single-pole double-throw (SPDT) analog switch that is designed to operate from 1.65 to 5.5 V. This device can handle both digital and analog signals, and signals up to V+ can be transmitted in either direction (see the TS5A3157 product page).

2.3.5 TMP007 or TMP006 Contactless Temperature Sensor

The TMP007 is a fully-integrated microelectromechanical system (MEMS) thermopile sensor that measures the temperature of an object without direct contact. The thermopile absorbs passive infrared energy from an object at wavelengths between 4 to 16 μm within the end-user defined field of view. The internal math engine combines the corresponding change in voltage across the thermopile with the internal cold-junction reference temperature sensor to calculate the target object temperature. The TMP007 also provides nonvolatile memory for storing calibration coefficients. The TMP007 can do the required calculations to take emissivity into account (see the TMP007 product page).

Alternatively, the TMP006 can be used when the target object temperature is being calculated by an external processor (see the TMP006 product page)

2.3.6 Design Enhancements

This section provides information on some of the design enhancements that can be made on this reference design.

2.3.6.1 TMP116 High-Accuracy Digital Interface Temperature Sensor

The TMP116 is a family of low-power, high-precision temperature sensors with integrated EEPROM memory. The TMP116 provides a 16-bit temperature result with a resolution of 0.0078°C and an accuracy of up to ±0.2°C with no calibration. The TMP116 is I^2C- and SMBus-interface compatible, has a programmable alert functionality, and can support up to four devices on a single bus (see the TMP116 product page).

2.3.6.2 Multichannel Remote Temperature Sensing Using TMP423

The TMP423 remote temperature sensor monitors with a built-in local temperature sensor. The remote temperature sensor with diode-connected transistors are typically low cost. The TMP423 includes series resistance cancellation, programmable non-ideality factor, wide remote temperature measurement range (up to 150°C), and diode fault detection. The ideality factor (η) is a measured characteristic of a remote temperature sensor diode as compared to an ideal diode. The TMP423 allow for different η-factor values (see the TPM423 product page).

2.3.6.3 Interfacing Multiple Sensors With Analog Output Sensor to Multichannel SAR ADC

When multiple sensors with an analog output are used in the reference design and depend on system performance (input from the current transformer, light, dust, pressure, and acoustic), the ADS7924 can be used for sampling all up to four inputs. A common gain amplifier can be used to provide gain to all the sensor input, simplifying the system design providing optimized cost solution. The ADS7924 is a four-channel, 12-bit ADC with an I^{2}C interface. With its low-power ADC core, support for low-supply operation, and a flexible measurement sequencer that essentially eliminates power consumption between conversions, the ADS7924 forms a complete monitoring system for power-critical applications such as battery-powered equipment and energy harvesting systems. Alarm conditions can be programmed that generate an interrupt. The combination of data buffering, programmable threshold comparisons, and alarm interrupts minimize the host MCU time needed to supervise the ADS7924 (see the ADS7924 product page).

2.3.6.4 Analog Input Sampling Using High Data Output ADC ADS7042

In applications requiring a higher sampling rate, the ADS7042 can be used. The ADS7042 is a 12-bit, 1-MSPS ADC. The device supports a wide analog input voltage range (1.65 to 3.6 V) and includes a capacitor-based SAR ADC with an inherent sample-and-hold circuit. The SPI-compatible serial interface is controlled by the CS and SCLK signals. The input signal is sampled with the CS falling edge, and SCLK is used for conversion and serial data output (see the ADS7042 product page).

2.3.6.5 ADS7142 ADC-Based Redundant Arc Flash Fault Sensing (Light and Temperature)

During an arc flash, there is increase in ambient light intensity and ambient temperature. Using a dual input ADC, both the inputs can be sensed and used for further analysis of arc flash fault sequence.

The ADC provides a digital alert output for an MCU interrupt and thresholds can be set for both ambient light and ambient temperature. Additionally, this device provides a programmable cycle count before the alert output for false trigger avoidance. The ADC can be configured in high precision mode, increasing the accuracy of the data measurement to a 16-bit accuracy. The ADS7142 provides diagnostics functionality by storing the conversion results in a data buffer in autonomous modes of operation. The data buffer can store up to 16 conversion results. The data buffer follows the first-in, first out (FIFO) approach and first provides the data that is stored first in the data buffer.

2.3.6.6 TI LED Driver and Transimpedance Amplifier Solutions for Arc Flash Fiber Loop Sensors

This reference design showcases solutions for arc flash point sensors. Another type of sensor commonly used to detect arc flash faults is the arc-flash fiber loop sensors. Arc flash fiber loop sensors are installed typically to cover a wider protected area with one fiber when no need for more exact fault location exists. Arc flash fiber loop sensors consist of an LED, photodiode, and transimpedance amplifier. The fiber is connected between the LED and the photodiode. TI solutions for arc flash fiber loop sensing include LED drivers and high-speed transimpedance amplifiers. Table 3 summarizes some of the TI selections for arc flash fiber loop sensors.

Table 3. TI Selections for Arc Flash Fiber Loop Sensors

DEVICE	TI DESIGN	DESCRIPTION
TPS43000	PMP30284	Tiny LED driver reference design
OPA320	TIPD176	1-MHz, single-supply, photodiode amplifier reference design
OPA857	TIDA-00978	Reference design for extending the OPA857 transimpedance bandwidth
TPS40195	PMP6692	LED driver 3.2 V at 0.5 A
TPS54610	PMP2440	Buck-boost (3.8 V at 1.5 A) for LED drivers
TPS92515	PMP15022	Advanced dimming capable buck LED driver reference design for industrial IR LED applications

2.3.6.7 Calibrating TMP007 Contactless Temperature Sensor

The TMP007EasyCalEVM is a hardware and software tool to facilitate finding calibration coefficients for use with the TMP007 in an application. The hardware included in this kit is an SM-USB-DIG board to interface a PC to the two-wire bus interface, a TMP007 PCB to take local and IR temperature measurements, and a TMP112 PCB to monitor remote object temperature. The software GUI operates the TMP007 and TMP112 devices to collect data for TMP007 calibration. It also analyzes the data captured by the TMP007EasyCalEVM hardware to generate coefficients and can analyze data captured by other systems without the hardware to generate coefficients (see the TMP007EasyCalEVM tool page).

2.3.6.8 Transimpedance Amplifier Selection

Transimpedance amplifier performance is critical for the response time of arc flash light sensing. Select an op amp depending on the response time requirement. Table 4 lists some op amps to consider for the design of the transimpedance amplifier.

Table 4. Transimpedance Amplifier Selections

SERIAL NUMBER	PART NUMBER	DESCRIPTION
1	OPA365	2.2-V, 50-MHz, low-noise, single-supply, rail-to-rail op amp
2	OPA354	250-MHz rail-to-rail CMOS single op amp
3	LMV791	17-MHz low-noise, CMOS input, 1.8-V operational amplifier with shutdown
4	OPA330	1.8-V, 35-µA, microPower precision, zero drift CMOS op amp
5	OPA348	1-MHz 45-µA RRIO single op amp

2.3.6.9 Onboard MCU Selection

TI provides the MSP430G23xx and MSP430FR21xx families of cost-optimized, small pin count MCUs that are well suited for a ambient light and temperature sensor module with an onboard MCU. Based on the interface required, consider the following devices listed in Table 5.

Table 5. MSP430 MCU Family Devices Selections

INTERFACE TYPE	DEVICES
SPI	MSP430G2332
	MSP430FR2111
	MSP430G2203
I^2C	MSP430G2332
	MSP430FR2111
	MSP430G2203
UART	MSP430FR2111
	MSP430G2203 or MSP430G2553

2.3.6.10 Arc Flash Fault Processing MCU Selection

To process an arc flash fault, including measuring the fault current and processing, consider the following MCUs listed in Table 6.

Table 6. Arc Fault Processing MCU Selections

SERIAL NUMBER	PART NUMBER	DESCRIPTION
1	MSP432P401R	SimpleLink, ultra-low-power, 32-bit, ARM Cortex-M4F MCU with 14-bit ADC, 128kB Flash, and 32kB RAM
2	MSP430F6779A	MSP430F6779A mixed signal microcontroller

2.3.6.11 Voltage Supervisors for MCU

The sensor module operates in harsh environments. To ensure that the MCU operates within a specified range, an external programmable-delay supervisory circuit is recommended. Consider the following devices listed in Table 7.

Table 7. Supervisor Selections

SERIAL NUMBER	PART NUMBER	DESCRIPTION
1	TPS3836	Nano-power supervisory circuits
2	TPS3837	
3	TPS3838	
4	TPS3839	Ultra-low-power, supply voltage supervisor
5	TPS3820	Voltage monitor with watchdog timer
6	TPS3808	Low-quiescent current programmable delay supervisor circuit

2.3.6.12 Interfacing to MCU With RF Capability CC1310, CC2640, or CC2650

The CC1310 is a member of the CC26xx and CC13xx family of cost-effective, ultra-low-power, 2.4-GHz and Sub-1 GHz RF devices. Very low active RF and MCU current consumption, in addition to flexible low-power modes, provide excellent battery lifetime and allow long-range operation on small coin-cell batteries and in energy-harvesting applications.

The CC2640 device is a wireless MCU targeting *Bluetooth*® applications. The device is a member of the CC26xx family of cost-effective, ultra-low-power, 2.4-GHz RF devices. Very low active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin-cell batteries and in energy-harvesting applications. The CC2640 device contains a 32-bit ARM® Cortex® M3 processor that runs at 48 MHz as the main processor and a rich peripheral feature set that includes a unique ultra-low-power sensor controller. This sensor controller is ideal for interfacing external sensors and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2640 device is ideal for a wide range of applications where long battery lifetime, small form factor, and ease of use is important.

The CC2650 device is a wireless MCU targeting Bluetooth, ZigBee® and 6LoWPAN, and ZigBee RF4CE remote control applications. The device is a member of the CC26xx family of cost-effective, ultra-low-power, 2.4-GHz RF devices. Very low active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin-cell batteries and in energy-harvesting applications. The CC2650 device contains a 32-bit ARM Cortex-M3 processor that runs at 48 MHz as the main processor and a rich peripheral feature set that includes a unique ultra-low-power sensor controller. This sensor controller is ideal for interfacing external sensors and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2650 device is ideal for applications within a whole range of products including industrial, consumer electronics, and medical.

2.3.6.13 Particle or Dust Sensing

One of the challenges with electrical equipments is they are placed in an outdoor environment and are exposed to dust, which degrades insulation or increases the contact resistance, causing overheating. Also during an arc flash along with heat, light, and pressure, dust is also generated. The TIDA-00378 reference design provides an analog front-end solution for measuring PM2.5 and PM10 particle matter. The design detects the light scattered by particles suspended in air. A sample software algorithm is provided to convert the analog output of the design into a particle size and concentration measurement. Test result data for cigarette smoke, Arizona dust, and mulberry pollen is provided along with all software and hardware design files. The dust-sensing transimpedance amplifier circuit consists of the OPA2320 and INA132 (see the TIDA-00378 PM2.5 and PM10 Particle Sensor Analog Front-End for Air Quality Monitoring Reference Design).

2.3.6.14 *Partial Discharge Sensing*

Partial discharge (PD) is a dielectric breakdown emerging locally within voids, cracks, bubbles, or inclusions of dielectric insulations or interfaces. The incurrence of PD is heavily affected by other influences such as the voltage and load current going across the line, temperature, humidity, vibration, and pressure. This reference design can be used to measure temperature, humidity, and pressure. The design also provides information on measurements of vibration using the TIDA-01471 Vibration Sensor Interface for PLC Analog Input Reference Design. Once started, PD will not stop again without actions. The consequences of continuous PD can result in energy loss (heat, sound, and light). This loss can destroy the insulation beginning at the small void and eventually to a complete electrical failure, or worse, to catastrophic impacts. This reference design can be used to sense heat, sound, and light providing protection to the power transformer or other substation switchgear failures due to PD.

2.3.6.15 *Acoustic: Microphone Input and Speaker Output Using Reference Design*

This reference design uses the high signal-to-noise ratio OPA322-based microphone stage to improve audio capture and provides an option to drive speaker using the LM4819 350-mW audio amplifier with shutdown mode (see the TIDM-TM4C129POEAUDIO Audio Communication With Power Over Ethernet (PoE) Reference Design for more details).

2.3.6.16 *Vibration Analysis During Arc Flash Fault Condition*

Industrial vibration sensing is a crucial part in condition monitoring, which is necessary for predictive maintenance. An integrated electronic piezoelectric (IEPE) sensor is the most common vibration sensor used in industrial environment. This design is a full analog front-end for an IEPE sensor interface that demonstrates how to achieve flexible high-resolution, high-speed conversion with low-power. Features include single-channel IEPE sensor analog input interfaced to programmable gain amplifier using the LMV751, third-order filter using the THS4551, 24-bit conversion resolution using the ADS127L01 with a programmable data rate of 265 to 32 kSPS to capture a 20-kHz bandwidth signal (see the TIDA-01471 Vibration Sensor Interface for PLC Analog Input Reference Design for more details).

2.3.6.17 *Daisy Chaining Multiple TMP107 Sensors*

In this reference design, two devices have been daisy chained and tested. More than two devices can be daisy chained. The TIDA-00800 reference design showcases a daisy-chained temperature sensor design for SensorTag. This design entails four temperature sensors along a daisy chain in a cabling environment. The sensors connect to the SensorTag development platform through the UART interface, where the information can be transmitted wirelessly. The Bluetooth low energy wireless technology makes testing and demonstration easier due to its integration in most modern equipment (see the TIDA-00800 Daisy chain temperature sensor reference design for SensorTag).

2.3.6.18 *Measuring Fault Current During Arc Flash Fault*

An arcing fault instantaneously produces light and heat radiation that can be detected by analyzing the visible light spectrum. Optical sensor-based arc flash protection can provide very short fault clearing time. However, overcurrent signature detection must be combined with the detection of the visible light (dual sensing) to avoid false tripping. Because a majority of arcing faults start as single phase faults, it is essential to analyze the neutral current signature as well. With neutral current measurement, it is possible to clear the fault in its early stages before a fault escalates to a phase-to-phase fault. Other reference designs can be leveraged for the design of the AC current and voltage measurement module (see the following reference designs: TIDA-00307 Analog Front End (AFE) for Merging Units and Multi-Function Protection Relays Reference Design, TIDA-00834 High Accuracy Analog Front End Using 16-Bit SAR ADC with ±10V Measurement Range Reference Design, and TIDA-00810 Reference Design to Measure AC Voltage & Current in Protection Relays w/Delta-Sigma Chip Diagnostics).

2.3.6.19 Arc Fault Sensor Module Interface to Fault Processing Base Unit (ARC Flash Fault Protection Relay)

This reference design showcases an I^{2}C interface between the sensor module and the base module. If reliable communication over a long distance is required, consider the RS-485 or CAN or serial interface with FO. The host MCU with an I^{2}C and UART interface can be used. Other reference designs can be leveraged for the design of the interface subsystem (see the TIDA-00308 Small Form Factor, Half-Duplex With Isolated & Non-Isolated RS485 Interface Reference Design and TIDA-01255 Automotive Reinforced Isolation CAN Reference Design).

2.3.6.20 Differential Light Measurement Using OPT101 and LED Output Regulation

The IN118 can measure difference output, and the LOG100 logarithmic amplifier can measure the log of ratio measurement (absorbance). To keep an LED (or other light) producing a constant amount of light over changing temperature and over the lifetime efficiency degradation of the LED, use a circuit similar to Figure 29 as shown in Section 9.2.4: LED Output Regulation Circuit of the OPT101 datasheet. As the efficiency of the LED degrades, this circuit increases the LED drive current to keep the output at the appropriate constant level. The circuit uses the OPA627 to drive the LED, and the OPT101 provides the feedback. This circuit can also be used in distributed temperature sensing for transmission lines (see Section 9.2.3: Differential Light Measurement of the device datasheet for more information).

2.3.6.21 Using External ALS

ALS's enable systems to sense and respond to light in ways similar to the human eye. With simple two-pin connections, these phototransistor-based sensors do not require an external amplifier. Some of the sensors to consider are the TEPT4400, TEPT5600, TEPT5700, TEMT6000, and TEMT6200F. The analog light sensor can be configured as a switch or interfaced to the ADC101C021 to measure light levels.

2.3.7 I^{2}C Interface and Registers Used for Different Sensors

This section explains the register configurations of the I^{2}C and UART-based temperature sensors.

2.3.7.1 I^{2}C Address Settings for Slave Devices

The I^{2}C addresses for the devices used in this reference design are listed in Table 8:

Table 8. ADC Register for Functional Testing

SERIAL NUMBER	DEVICE	ADDRESS
1	ADC101C021	0x54
2	BMP280	0x77
3	DAC101C081	0x0D
4	HDC1080	0x40
5	OPT3001	0x44
6	TMP007	0x41
7	TMP102	0x49
8	TPL0401A	0x2E
9	TMP175	0x37

2.3.7.2   *I²C Interface Device Configurations*

This section details the I2C register configuration for different devices.

2.3.7.2.1   *ADC101C021 SAR ADC*

Table 9 details the ADC101C021 configuration used to test its performance.

Table 9. ADC101C021 Configuration

SETTINGS	DESCRIPTION
Flags	The flags for alert output have been set as: • Alert Flag—Enabled • Alert Pin—Enabled • Polarity—Active high
Reading the conversion result	The conversion result register [0x00] is a 16-bit register, which holds the result of the most recent conversion. D2 to D11 is the conversion result, and D15 is the alert flag.
Alert limit registers	There are two alert limit registers, one for under range and the other for over range: • VLOW Alert Limit Register Under Range [0x03]: This register holds the lower limit threshold used to determine the alert condition. If the conversion moves lower than this limit, a VLOW alert is generated • VHIGH Alert Limit Register Over Range [0x04]: This register holds the upper limit threshold used to determine the alert condition. If the conversion moves higher than this limit, a VHIGH alert is generated.
Hysteresis registers	This register holds the hysteresis value used to determine the alert condition. After a VHIGH or VLOW alert occurs, the conversion result must move within the VHIGH or VLOW limit by more than this value to clear the alert condition.

2.3.7.2.2   *DAC101C081 DAC Output*

Table 10 details the DAC101C081 configuration used to test its functionality.

Table 10. DAC101C081 Configuration

SETTINGS	DESCRIPTION
Default register settings	The DAC101C081 has a single 16-bit DAC register, which holds the input data bits and the mode selection bits with normal operation mode (no resistors connected to GND) and a 10-bit input resolution
Writing digital data	The input is a direct value in the range (0 to 1023). The output of the DAC is based on Equation 01 in Section 9.3.1 of the DAC101C081 datasheet (SNVS801).

2.3.7.2.3   *HDC1080 Humidity and Temperature Sensor*

Table 11 details the HDC1080 configuration used to test its functionality.

Table 11. HDC1080 Configuration

SETTINGS	DESCRIPTION
Default registers settings	Corresponding bits for the following configuration is configured in register [0x02] with the temperature and humidity mode, heater enabled, 14-bit temperature resolution, and 14-bit humidity resolution.
Enable	CMD_HDC1080_ON command is used to configure the HDC1080.
Reading humidity	The raw humidity value from the HDC1080 is printed in the UART terminal and converted into relative humidity value in the application. Section 8.6.2 of the HDC1080 datasheet is used to convert the raw data into relative humidity.
Reading temperature	The raw temperature value from HDC1080 is printed in UART terminal and converted into relative humidity value in the application. Section 8.6.1 from the HDC1080 datasheet is used to convert the raw data into the equivalent temperature value

2.3.7.2.4   OPT3001 Digital Light Sensor

Table 12 details the OPT3001 configuration used to test its performance.

Table 12. OPT3001 Configuration

SETTINGS	DESCRIPTION
Default register settings	Corresponding bits for the following configuration is configured in register [0x01] with the conversion time set to 100 ms, mode of conversion set to continuous conversion, and auto range.
Enable or disable	CMD_OPT3001_ON/ CMD_OPT3001_OFF command is used to enable or disable OPT3001. Conversion mode bits of Configuration register [0x01] is set to zero to disable the OPT3001.
Reading intensity	When the OPT3001 is enabled for every ≈ 200 ms, a light intensity is measured. The read value is printed in the UART terminal and then converted into an equivalent lux value in the application. Equation 03 from the OPT3001 datasheet is used to convert the register data into the equivalent lux value.
Alert threshold registers	There are two threshold registers (16-bit) in the OPT3001: • Low-limit register: This register sets the lower comparison limit for the interrupt reporting mechanism. • High-limit register: The high-limit register sets the upper comparison limit for the interrupt reporting mechanism.

2.3.7.2.5   TMP007 Contactless Temperature Sensing

Table 13 details the TMP007 configuration used to test its functionality.

Table 13. TMP007 Configuration

SETTINGS	DESCRIPTION
Default register settings	Corresponding bits for the following configuration is configured in register [0x02] with the total conversion time set to 260 ms, conversion mode on, and INT/COMP set to interrupt mode.
Reading temperature	The read value from the TMP007 is printed in the UART terminal and converted into an equivalent temperature value. Section 7.3.7 from the TMP007 datasheet is used to convert the register data into the equivalent temperature value.
Alert threshold registers	There are two threshold registers (16-bit) in the TMP007: • Object temperature low-limit register: This register sets the lower comparison limit for the interrupt reporting mechanism. • Object temperature high-limit register: The high-limit register sets the upper comparison limit for the interrupt reporting mechanism.
Coefficient registers	All the coefficient registers values are defined in an app.h file. For further details on the coefficient registers of the TMP007, see Section 7.5.11 of the TMP007 datasheet. The coefficient values can be changed during the compile time by defining the desired coefficient values in the "app.h" header file.
Calibration coefficient SO	The purpose of the object is to adjust FOV and emissivity of object. The calibration value is application and object dependent; by default, values are based on a black body with $\varepsilon = 0.95$ and 110° FOV.

2.3.7.2.6 TMP102 Onboard Temperature Sensor

Table 14 details the TMP102 configuration used to test its performance.

Table 14. TMP102 Configuration

SETTINGS	DESCRIPTION
Default register settings	Corresponding bits for the following configuration is configured in register [0x01] with a conversion rate of 4 Hz, a resolution of 12 bits, and normal mode.
Enable or disable	CMD_ TMP102 _ON/CMD_ TMP102 _OFF command is used to enable or disable the TMP102. Shutdown mode bit of Configuration register [0x01] is set to zero to disable TMP102.
Reading temperature	The read value from TMP102 is printed in the UART terminal and converted into equivalent temperature value. Section 7.3.1 of the TMP102 datasheet is used to convert the register data into equivalent temperature value.
Alert threshold registers	There are two threshold registers (16-bit) in the TMP102: • Low-limit register: This register sets the lower comparison limit for the interrupt reporting mechanism. • High-limit register: The high-limit register sets the upper comparison limit for the interrupt reporting mechanism.

2.3.7.2.7 TPL0401A Digital Potentiometer

Table 15 details the TPL0401A configuration used to test its performance.

Table 15. TPL0401A-10 Configuration

SETTINGS	DESCRIPTION
Default settings	The digital potentiometer is set as Rheostat Mode B and a max resistance of 10 kΩ.
Setting resistance	The decimal code of the wiper is received through the UART terminal. Rheostat Mode B from the TPL0401A datasheet is used to convert the resistance value into an equivalent decimal value of the wiper code.

2.3.7.2.8 TMP175 High-Accuracy Onboard Temperature Sensor

Table 16 details the TMP175 configuration used to test its functionality.

Table 16. TMP175 Configuration

SETTINGS	DESCRIPTION
Default register settings	Corresponding bits for the following configuration is configured in register [0x01] with a conversion time of 220 m, a resolution of 12 bits, and comparator mode.
Enable or disable	CMD_ TMP175 _ON/CMD_ TMP175 _OFF command is used to enable or disable the TMP175. Shutdown mode bit of the configuration register [0x01] is set to zero to disable the TMP175.
Reading temperature	The read value from the TMP175 is printed in the UART terminal and converted into an equivalent temperature value. Section 7.3.1 from the TMP175 datasheet is used to convert the register data into the equivalent temperature value.
Alert threshold registers	There are two threshold registers (16-bit) in the TMP175: • Low-limit register: This register sets the lower comparison limit for the alert mechanism • High-limit register: The high-limit register sets the upper comparison limit for the alert mechanism.

2.3.7.2.9 TMP107 Remote Temperature Sensor

Table 17 details the TMP107 configuration used to test its functionality. This device communicates using SMAART wire protocol, and multiple TMP107 devices can be connected in a daisy chain.

Table 17. TMP107 Configuration

SETTINGS	DESCRIPTION
Default register settings	Corresponding bits for the following configuration is configured in register [0x02] with a rate of 1 conversion/second, continuous conversion mode, alert mode enabled, and alert logic set to active low.
Reading temperature	The read value from the TMP107 is printed in the UART terminal and converted into an equivalent temperature value. Section 7.3 from the TMP107 datasheet is used to convert the register data into the equivalent temperature value.
Alert threshold registers	There are four threshold registers (16-bit) in the TMP107: • Low_Limit_1_Register: This register sets the lower comparison limit for the Alert-1 interrupt reporting mechanism • High_Limit_1_Register: This register sets the higher comparison limit for the Alert-1 interrupt reporting mechanism • Low_Limit_2_Register: This register sets the lower comparison limit for the Alert-2 interrupt reporting mechanism • High_Limit_2_Register: This register sets the higher comparison limit for the Alert21 interrupt reporting mechanism.

3 Hardware, Testing Requirements, and Test Results

3.1 Required Hardware

Table 18 details the connections between the MCU board and the sensor board.

Table 18. MCU Host to TIDA-00811 Interface

MSP430 LAUNCHPAD	TIDA-00811	DESCRIPTION
P2.1 (UCA0RXD)	—	UART-RX for PC communication
P2.0 (UCA0TXD)	—	UART-TX for PC communication
P2.6 (UCA1RXD)	J2-Pin1	UART-RX for SMAART wire (TMP107)
P2.5 (UCA1TXD)	J2-Pin2	UART-TX for SMAART wire (TMP107)
P1.6 (UCB0SDA)	J1-Pin4	I^2C SDA line for sensor interface
P1.7 (UCB0SCL)	J1-Pin3	I^2C SCL line for sensor interface
P1.0	—	General purpose output
P1.1	—	General purpose output
P1.2	—	General purpose input
P1.3	—	General purpose input

3.2 Testing and Results

3.2.1 Test Setup

Figure 6 shows the setup used for functional and performance testing of the AC/DC binary input module (BIM). The setup for testing the sensor board consists of the following:

- A sensor board with the option to sense ambient light, temperature, and humidity
- MCU interface with UART, I^2C, and GPIO ports connected
- DC power supply or power derived from the MCU LaunchPad™
- MSP430FR5739 experimenter board with MSP430FR5729 MCU mounted

Figure 6 shows the connections made to test the TIDA-00811 sensor board.
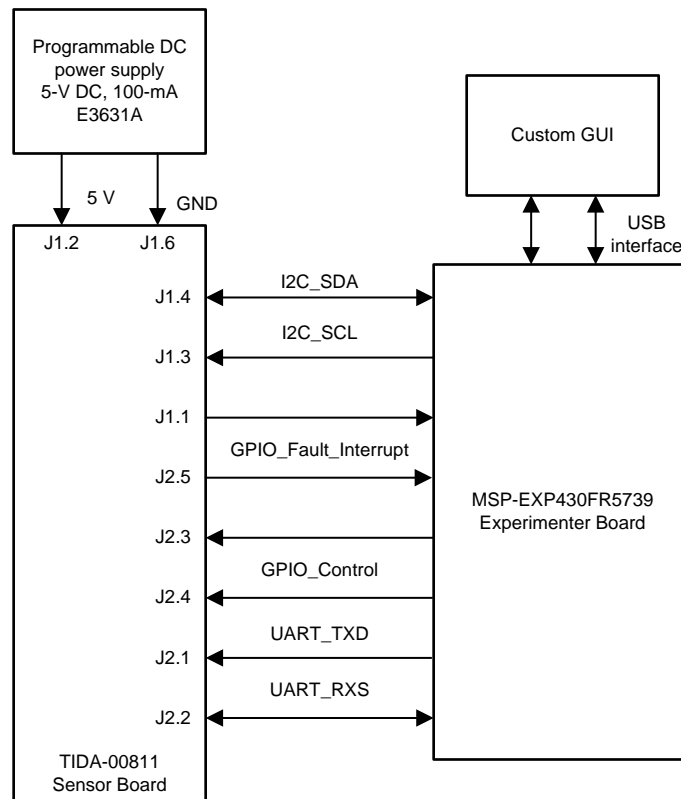
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Figure 6. Setup for Testing Sensor Module

3.2.2 Functional Testing

Table 19 details the different functional tests performed on the sensor board.

Table 19. Functional Test Observations

PARAMETER	SPECIFICATION	MEASUREMENT
3.3-V power supply	3.3 V	3.36 V
I^{2}C interface	Operate as expected	OK
I^{2}C interface with >10-m cable	Operate as expected	OK
Light sensor output	As per the device specification	OK
Analog temperature sensor output	As per the device specification	OK
Temperature switch	As per the device specification	OK
Digital temperature sensor	As per the device specification	OK
Humidity plus temperature	As per the device specification	OK
Remote temperature sensing	As per the device specification	OK
Contactless temperature sensing	As per the device specification	OK
Sensor alert output	Based on the set level	OK
Pressure sensing	As per the device specification	OK
ALS with integrated transimpedance amplifier	As per the device specification	OK

3.2.3 Temperature Measurement

This section details the different tests performed for temperature sensors.

3.2.3.1 Temperature Performance Testing

Table 20 summarizes the different tests done for temperature sensors.

Table 20. Temperature Test Summary

SENSOR	TEMPERATURE	OBSERVATION
TMP175, TMP102, TMP175, TMP107, TMP007, HDC1080	0°C	OK
	25°C	OK
	60°C	OK

3.2.3.2 Room Temperature Measurement

Table 21 provides the temperature measurement data for different sensors.

Table 21. Temperature Measurement at Room Temperature

SENSOR	REFERENCE TEMPERATURE	MEASURED TEMPERATURE
TMP175	25.5°C	24.70°C
TMP102	25.5°C	26.20°C
TMP107_1	25.5°C	25.40°C
TMP107_2	25.5°C	25.80°C
TMP007	25.5°C	25.03°C
HDC1080	25.5°C	25.71°C

3.2.4 Performance Testing

This section details the performance tests performed on the light and temperature sensor module.

3.2.4.1 Analog Output From OPT101

Table 22 shows the voltages at different light levels.

Table 22. Summary of OPT101 Testing

TEST CONDITION	OBSERVATION
Dark	OK
Normal	OK
High intensity	OK

3.2.4.2 ADC and DAC Measurement

Table 23 summarizes the ADC performance used to measure the light sensor output and DAC performance used to set the light intensity level.

Table 23. ADC and DAC Measurement Results

ACTUAL VOLTAGE (mV)	DAC OUTPUT (mV)	ADC VOLTAGE (mV)	DAC ERROR	ADC ERROR
100	99.2670	98.455	–0.733%	–0.818%
250	252.0245	251.720	0.810%	–0.121%
500	502.7295	503.440	0.546%	0.141%
1000	1009.9250	1013.985	0.992%	0.402%
2500	2520.2450	2531.410	0.810%	0.443%
3000	3025.7150	3038.910	0.857%	0.436%

3.2.4.3 Digital Potentiometer Control

Table 24 details the potentiometer tests performed.

Table 24. Digital Potentiometer Performance

RESISTANCE (Ω)	EXPECTED VOLTAGE (mV)	ADC INPUT (mV)
500	336	342.5
1000	614	625.0
2500	1146	1169.0
5000	1701	1712.0
10000	2245	2245.0

NOTE: Adjust the potentiometer tap based on the required voltage. 4.7K is used as an external voltage divider. To increase the output range and sensitivity, reduce the external divider resistor to 1 kΩ or as required after testing.

3.2.4.4 Transimpedance Amplifier Performance

This circuit consists of a single-supply op amp configured as a transimpedance amplifier with a bandwidth greater than 1 MHz for amplifying the light-dependent current of a photodiode. A small bias voltage is derived from the positive supply and applied to the non-inverting input of the op amp. This prevents the output from saturating at the negative supply rail in the absence of input current. This circuit is designed to produce output voltages of 0.1 to 4.9 V for photodiode currents of 0 to 90 µA. This circuit is designed for use in common trans-impedance amplifier applications such as barcode scanners, optical networking, and spectrometers. A 5-V power supply can be connected to the op amp for measuring a wider range of input. The design is based on the TIPD176 reference design.

3.2.4.5 Onboard Self-Diagnostic

Table 25 summarizes the diagnostic tests performed on the reference design board.

Table 25. Summary of TIDA-00811 Sensor Board Diagnostics

TEST CONDITION	OBSERVATION
Light sensing	OK
Humidity and temperature sensor	OK

3.2.5 Test Results Summary

Table 26 summarizes the test performed on the temperature and ambient light sensing reference design.

Table 26. Test Results Summary

TEST	OBSERVATION
ADC101C021 or ADC101C027	OK
OPA320-based transimpedance amplifier	OK
DAC101C081, TPL0401A-10	OK
OPT101P-J	OK
PCA9515ADR	OK
HDC1080	OK
TMP102, TMP175	OK
LMT87, LM35	OK
TMP007	OK
TMP107, Single and daisy chain	OK
TMP302	OK
MCU interface using I^{2}C and GPIO	OK

4   Design Files

4.1   Schematics

To download the schematics, see the design files at TIDA-00811.

4.2   Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00811.

4.3   PCB Layout Recommendations

4.3.1   Layout Prints

To download the layer plots, see the design files at TIDA-00811.

4.4   Altium Project

To download the Altium project files, see the design files at TIDA-00811.

4.5   Gerber Files

To download the Gerber files, see the design files at TIDA-00811.

4.6   Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00811.

5   Related Documentation

1. Texas Instruments, *MSP-EXP430FR5739 FRAM Experimenter Board User's Guide* (SLAU343)
2. Texas Instruments, *1 MHz, Single-Supply, Photodiode Amplifier Reference Design*, TIPD176 Design Guide (TIDU535)
3. Texas Instruments, *IR Temperature Sensor FAQ*, TI E2E Community (https://e2e.ti.com/support/sensor/temperature_sensors/f/243/t/548824)

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6   Terminology

BIM— Binary input module

MCU— Microcontroller unit

ALS — Ambient light sensor

FO— Fiber optic

AFD— Arc flash detection

7   About the Authors

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