Smart fault indicators with ultra-low power microcontrollers

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A fault indicator is a device used in electric power distribution networks on overhead lines and underground cables to detect and indicate fault conditions.

A fault indictor installed on an overhead power line is shown in **Figure 1** as an example. At the bottom of the fault indicator, there is a light-emitting diode (LED) light. The LED will be turned on when there is an overcurrent condition. The fault indicator makes the failure visible to field crew members at a distance to identify the point of failure. When properly installed, fault indicators reduce operating costs and service interruptions by providing information to identify the section of the network that has failed. At the same time, the device increases safety and reduce equipment damage by reducing the need for hazardous fault diagnostic procedures. Fault Indicators, due to their location, are primarily battery powered; hence low-power operation is highly desirable. This paper will provide a guide on how to build a smart fault indicator using ultra-low-power microcontrollers (MCUs). In addition, fault indicators have the option of wireless connectivity for communication to remote hand-held devices and/or terminal units at the base of the electric poles or structures.

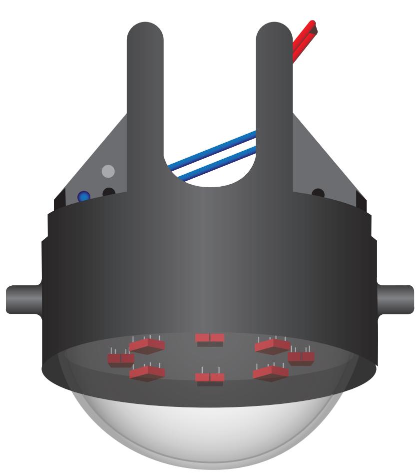

Figure 1. *Example of an overhead fault indicator*

Enabled by the recent developments of the ultra-low power microcontrollers and wireless connectivity technology, the "smart" fault indicators have been developed. **Figure 2** illustrates an example of a smart fault indicator system scenario.

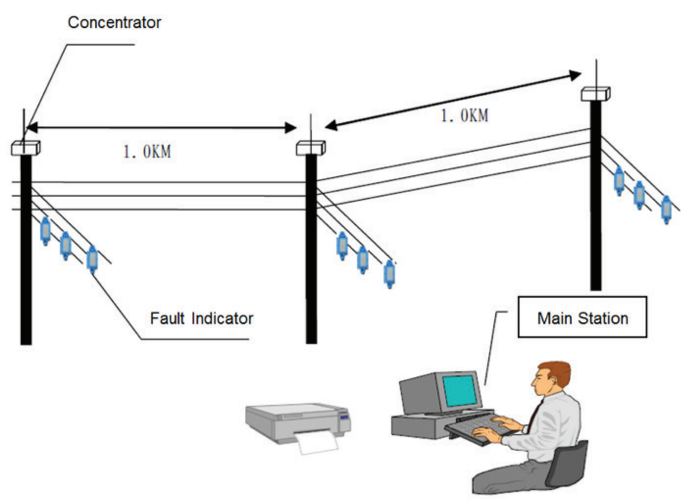

Figure 2. *A smart fault indicator system*

In **Figure 2**, the fault indicators are installed on the junctions of the overhead power line network. The measurement data of temperature and the current in power transmission lines are wirelessly sent to the remote terminal unit/terminal units mounted on the poles. The remote terminal units (RTUs) use a GSM modem to pass the data to the cellular network to relay the real-time information to the main station. The main station can also control and run diagnostics on the fault indicators via the same data path. In the case of an underground cable, the fault indicators are connected to the RTU via a wired network such as RS-485.

The smart fault indicator can also be called "connected" fault indicators because it can be connected to the main station all the time. Connecting to the main station all the time has several advantages. The first one is remotely monitoring the fault conditions from the main station. The crew members from the utility company do not need to go in the field to find the fault location. The smart fault indictor is also capable of constantly monitoring the temperature and current so that the controller at the main station has a real-time status of the power distribution network. With those additional pieces of information, the power utility providers are able to quickly identify the fault location, minimize the power down time and even take actions before the failure occurs. Furthermore, people at the main station can run diagnostics on the fault indicators at required intervals to make sure they work correctly.

Since the fault indicators are battery powered and installed on power lines, the primary system requirement is ultra-low power consumption. Choosing the right microcontroller has become one of the most important decisions. In addition to the conventional control-oriented functions, highly integrated analog circuits in an MCU have contributed to reducing the size of external analog front-end circuits and the total system power consumption dramatically. The quality of a fault indicator, thus, is determined by the features supported by the MCU inside a fault indicator. The purpose of this document is to show the benefits of MSP430™ FRAM microcontrollers in a fault indicator. In addition to ultra-low power consumption, the ferroelectric random access memory (FRAM) memory is capable of fast data logging and retaining the data in power-loss conditions. TI solutions for energy harvesting and wireless communication will also be briefly reviewed.

Smart fault indicator functional blocks

The functional block diagram of the smart fault indicator based on TI MSP430 FRAM microcontroller is shown in **Figure 3**. The current transducer produces an analog voltage which is proportional to power line current. This voltage signal will be conditioned (amplified and filtered) by the op amp. The output of the op amp is sampled by the analog-to-digital converter (ADC) on the MCU. Data analysis is then performed on the digital stream from the ADC. In **Figure 3**, the op amp output is also routed to a comparator on the MCU. The comparator will generate a flag to the CPU in the microcontroller if the input level is beyond a predetermined threshold.

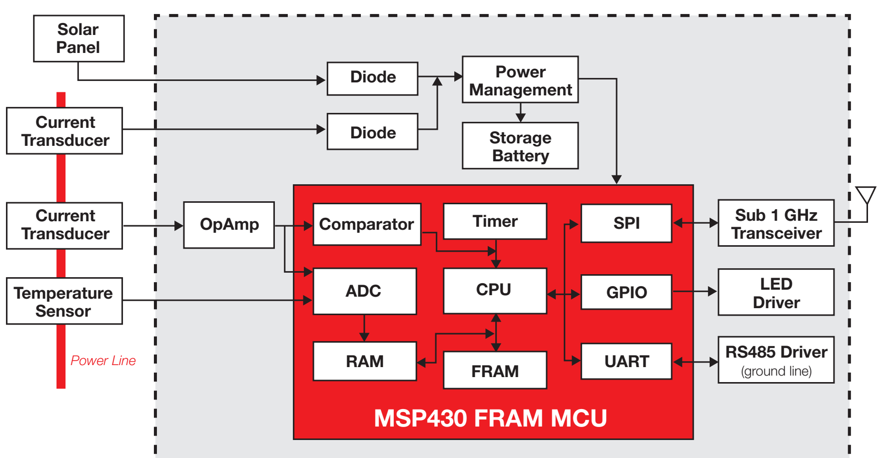

Figure 3. *Functional block diagram of a smart fault indicator based on MSP430 FRAM MCU*

The analysis of the current measurement can be done in the time domain or frequency domain. In the cases that the current waveform on the power line is far from a sine wave and the irregularity in the waveform is a concern, a spectrum analysis is sometimes more straightforward to evaluate the line status.

If the maximum frequency of interest is 100 Hz, the line current needs to be sampled at least every five milliseconds. A 64 point fast Fourier transform (FFT) will provide a spectrum covering 0-100 Hz with a resolution of 3 Hz. It takes the MSP430 microcontroller CPU at 16 MHz about one millisecond to perform such FFT. A low-pass filter needs to be implemented with an op amp to eliminate the aliasing caused by high frequency noise. The result of spectrum analysis is used to determine if the line current is in normal condition.

The line temperature is also an important data point related to power line health. The temperature sensor output is normally a voltage and can be directly sensed by the ADC on the MCU.

After the processing is complete, the fault indicator sends the output data to the RTU through the wireless link. Sub-1 GHz connectivity technology is normally chosen to achieve the required transmission distance while minimizing power consumption. For ground lines, the data can be outputted to a RS485 interface. The MCU may need to encrypt the data per the security requirements of the system. A traditional LED light will be turned on when the fault indicator detects a failure condition.

The fault indictor is a battery operated device. It is installed on either overhead power transmission lines or underground power cables. The access is very limited once installed. Therefore, it is critical to have a long battery life. Two steps can be taken to minimize the power drawn from the battery.

1) Take advantage of low-power modes of microcontrollers.

The MCU can be put into low-power mode during the time intervals between taking line current samples and when the data processing is not needed. The op amp should also be turned off in this period of time. The current consumption of the MSP430 FRAM MCU in standby mode is in the range of 0.4 uA ~ 1 uA.

(2) Use energy harvesting.

The block diagram in Figure 3 shows two possible sources for energy harvest: solar panel and power transmission line (via a current transducer). The power management device is specially designed to extract microwatts (μW) to milliwatts (mW) of power generated from a variety of high output impedance direct current (DC) sources like a solar panel. The battery management features ensure that the storage battery is not overcharged by the extracted power. It also integrates a highly efficient nano-power buck converter for providing a second power rail to the target system.

MSP430 FRAM Microcontrollers

The MSP430 ultra-low-power FRAM MCUs are recommended for the fault indicator application because they combine uniquely embedded FRAM and a holistic ultra-low-power system architecture, allowing innovators to increase performance at lowered energy budgets. FRAM technology combines the speed, flexibility and endurance of SRAM with the stability and reliability of Flash at a much lower power. A complete list of the MSP430 FRAM microcontroller family can be found at www.TI.com/fram.

The MSP430FR58/59xx FRAM MCU family offers the following benefits to smart fault indicator applications.

- 16-Bit RISC architecture up to 16 MHz clock with optimized ultra-low power mode consumption.
  - Active mode: Approximately 100 µA/MHz
  - Standby mode: 0.4 uA ~ 1uA
- Up to 256 KB of FRAM.
- High-performance analog
  - Analog comparator that can be used to check if the input is within a predetermined range
  - 12-Bit ADC for reading the analog inputs to digital stream for data processing
- 128/256-Bit AES and 16/32 bit CRC accelerator for security encryption/decryption and data integrity check.
- Multiple UART/SPI/I2C ports for communication.

In addition to the features common to the FRAM MCU family, the flagship device, MSP430FR5994 MCU, includes a low energy accelerator (LEA) for signal processing module to offer advanced digital signal processing (DSP) capabilities for ultra-low power applications.

The low-energy accelerator for signal processing or LEA is a TI proprietary accelerator designed to efficiently perform vector based arithmetic and signal conditioning. The most common LEA operations include FFT, finite impulse response filter (FIR), infinite impulse response filter (IIR) matrix multiply, addition, and subtraction.

The LEA module executes completely independent of central processing unit (CPU). The LEA module can operate when the CPU is in low-power mode. The LEA peripheral consumes only 67uA/MHz, which is about 30 percent less than CPU. For example, the LEA module takes only 3060 cycles to complete a 128 complex point FFT. For the same calculation, it takes an MSP430 MCU's CPU with DSP library about 34960 cycles. The LEA module only takes about six percent of energy compared with other MSP430 MCU CPUs for completing 128 complex point FFT. These advantages make the LEA module a great choice when intensive math operation is needed.

To make it easier for a customer developing products with TI MCUs, the microcontroller LaunchPad™ Development Kit is designed as an easy-to-use evaluation module. For more information about TI MCU LaunchPad kits, visit www.ti.com/launchpad.

In addition to the hardware tools, TI also provides a software library which offers comprehensive software for setting up the peripheral modules on the MSP430 MCUs called MSPWare library.

Energy harvesting and communication

Power management for energy harvesting

TI offers an extensive family of ICs for harvesting energy from solar and other sources. The bq25570 device is specifically designed to efficiently extract microwatts to mW of power generated from a variety of high output impedance DC sources like photovoltaic (solar) or thermal electric generators (TEG) without collapsing those sources. The battery management features ensure that a rechargeable battery is not overcharged by this extracted power, with voltage boosted or depleted beyond safe limits by a system load. In addition to the highly efficient boosting charger, the bq25570 integrates a highly efficient, nano-power buck converter for providing a second power rail to systems such as wireless sensor networks which have stringent power and operational demands. All the capabilities of bq25570 are packed into a small foot-print 20-lead 3.5-mm × 3.5-mm QFN package (RGR).

The Energy Harvester BoosterPack™ plug-in module reference design is an evaluation module using bq25570 which harvests energy from a wide variety of current sources or from the onboard solar cells to power any low-power TI LaunchPad kit. This design is a highly integrated power management solution that is well-suited for ultra-low power applications.

Sub-1 GHz transceiver

TI offers Sub-1 GHz solutions that consist of a fully integrated single-chip radio transceiver designed for high performance at very low-power and low-voltage operation in cost-effective wireless systems. All filters are integrated, thus removing the need for costly external surface acoustic wave (SAW) and intermediate frequency (IF) filters. The device is mainly intended for industrial, scientific, and medical (ISM) and short range device (SRD) frequency bands at 164 to 192 MHz, 274 to 320 MHz, 410 to 480 MHz, and 820 to 960 MHz.

The CC1120-CC1190 BoosterPack plug-in module based on the TI Sub-1 GHz CC1120 RF transceiver is designed to work with the MSP430 MCU LauchPad development kits, as well as work as a stand-alone module by using SmartRF™ application software. The CC1190 device is a wireless range extender. The module is equipped with an integrated PCB trace antenna which operates in the United States at 902~928MHz and in Europe at 869~870MHz ISM frequency bands.

RS485 transceiver

When the smart fault indicator is installed on ground lines, the RS485 link is often used for the communication with the transmitter unit. The SN65HVD72EVM helps designers evaluate the device performance, supporting fast development and analysis of data transmission systems using the SN65HVD7x family of RS485 transceivers. The evaluation module (EVM) board comes with the SN65HVD75 (20Mbps) device soldered to the board. The EVM kit includes an IC sample pack with the SN65HVD72 (250kbps) and the SN65HVD78 (50Mbps) device. Either device can be evaluated by replacing the SN65HVD75 with the desired speed grade device.

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