A small-footprint PoE solution for machine-vision cameras and sensors

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Introduction

Power over Ethernet (PoE) is a technology with an increasing number of products on the market. Small devices with low power consumption are getting more equipped with PoE. This article describes the important aspects when implementing PoE for 10/100 Ethernet and Gigabit Ethernet and also features an example implementation for a small-footprint design for machine-vision cameras.

Machine vision is becoming more popular in factory automation. In addition to reading codes, cameras can also identify objects, conduct quality tests and control processes. Because of these quality tests and control of processes, there is real demand to have a 100% quality check for the production line.[1]

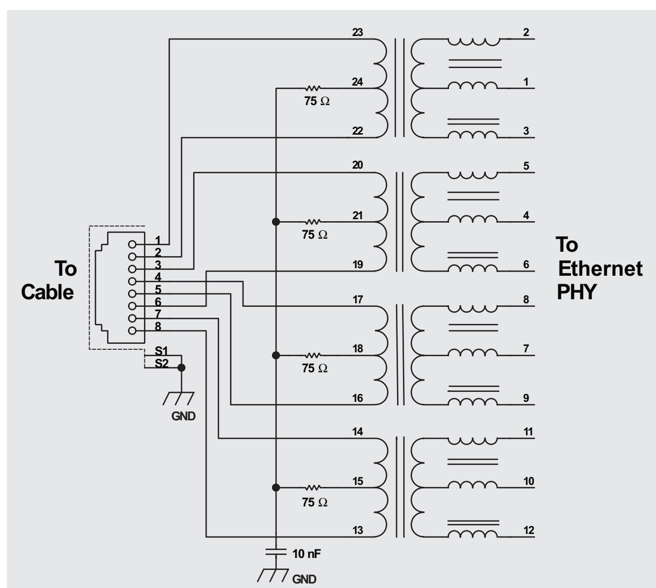
A vision camera simply delivers a raw image of an object. Most modern vision cameras come in a very small footprint (29 x 29 x 29 mm) with all electronics, including the interfaces, located in a small housing.[2] Complementary metal-oxide semiconductor (CMOS) sensors that are used in such cameras are sensitive to heat. Because the image quality degrades with higher temperatures, it is important to keep the power dissipation low. A small housing with no room for a fan or heat sink doesn't allow the dissipation of a lot of heat, so the power is very limited. It is still necessary to include a CMOS sensor and a field-programmable gate array (FPGA) or processor, as well as a high-speed interface and the necessary power supply. The electronic system has to be able to capture, process and transmit uncompressed video frames at high frame rates and resolutions. Often, the full data rate of the interface is used and can be the limiting factor. Common interfaces include USB 3.x, Gigabit Ethernet or even 10-Gigabit Ethernet. Both Gigabit interfaces usually come with power over Ethernet (PoE). Gigabit Ethernet is a great way to transmit high data rates and power over cable lengths as long as 100 meters.

A vision sensor differs from a vision camera in that processing is integrated; it occurs in the same location as the sensor. Vision sensors are more relaxed in terms of size and power. These devices are larger and can even have a heat sink. In addition to the components in the camera, vision sensors also include lighting[3] and a powerful processor. Because the output data is processed data rather than a raw image, the necessary data rate is usually lower. Although vision sensors use 10/100 Ethernet with industrial protocols, PoE is also used.

PoE basics

Adding PoE to an Ethernet system requires some modifications.[4] Figure 1a shows how the transformers are usually connected in a non-PoE application with Gigabit Ethernet. The middle taps of the transformers are connected to each other through 75-Ω resistors and to GND by a capacitor; this circuit is typically called a Bob Smith termination. In this case, GND is typically the housing of the system or the shield of the cable. As shown in Figure 1a, it is not possible to supply power through the Ethernet cable to power the device.

Figure 1a. Magnetics without PoE



To create the ability to inject power, Figure 1b shows that adding one capacitor per middle tap interrupts the DC path. Since the DC path is no longer shorted, a DC voltage can be applied symmetrically between each differential pair. In total, it is possible to have up to four pairs of twisted cable. These pairs go to the powered-device (PD) controller over two rectifier bridges. By using a rectifier, the polarity as well as the pairs used does not matter.

The device delivering power, the power sourcing equipment (PSE), has to make sure that a PoE-capable PD is connected before powering it so as not to damage it. There are a few passive PoE implementations on the market that just connect a power supply to the middle tap of a transformer without any detection. This works when used with a PoE PD, but could damage anything else.

Detecting a PD

The PSE has to detect whether there is a valid PD connected. In 2003, the Institute of Electrical and Electronics Engineers (IEEE) 802.3af standard defined how this detection and classification should look, limiting power to 15.4 W at the PSE output. In 2009, IEEE 802.3at extended this limit by an additional class, such that a PSE can deliver up to 30 W. In addition to hardware signaling for the power level, the standard defines a protocol on data link layer 2.

When connecting a PD to a PSE, the first step is detection by the PSE. During this step, a low voltage drop between 2.7 V and 10.1 V is developed over the PD to sense a signature resistor. Figure 2 shows the complete procedure of an IEEE 802.3af-compliant Class-3 PD. The detection of the signature resistance (in the range of 19 kΩ to 26.5 kΩ) occurs over four steps in order to make it robust.

After correct detection of the signature, the classification starts. The PSE increases the voltage into a voltage range of 15.5 V to 20.5 V; the PD then has to draw a constant current to signal its power needs. For example a current of 0 mA is a valid classification—meaning Class 0 or a non-implemented classification—which translates to 15.4 W of power coming from the PSE.

The example in Figure 2 starts with a voltage between 5 V and 8 V; during this time the signature is detected. After successful detection, the voltage increases to 19 V and the PD draws a current of 28 mA. The PSE now knows that there is a Class-3 device connected and will provide up to 15.4 W. The PSE turns on the full supply voltage, which can be between 44 V and 57 V for type 1.

Figure 1b. Magnetics with PoE

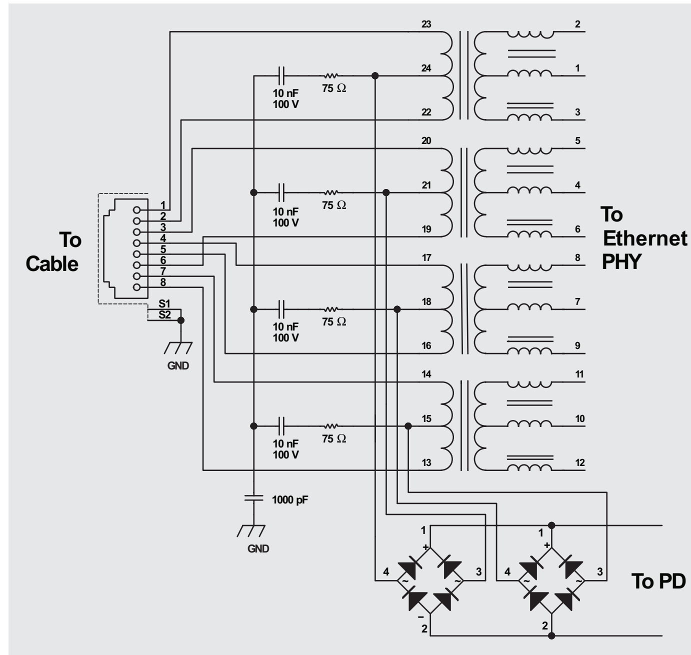
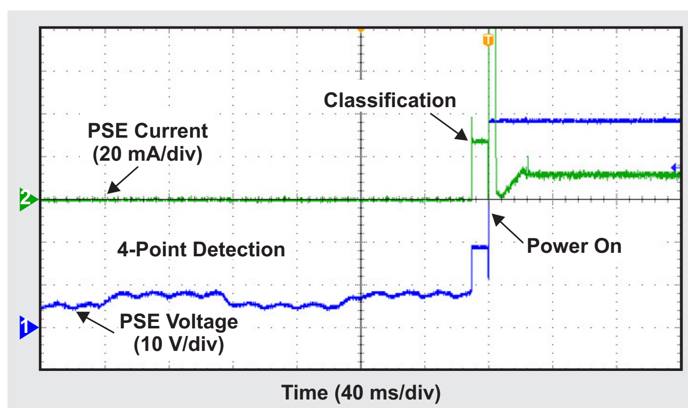


Figure 2. Detection and classification



For IEEE 802.3at devices, this procedure is extended. A first classification with a current of 36 mA to 44 mA signals Class 4 IEEE 802.at devices and must be followed by a second classification. This power class allows up to 30 W.[5]

Table 1 details the power-up stages, and Table 2 lists the classifications and currents.

10/100 Ethernet versus Gigabit Ethernet

The use of the cable and the signaling between 10/100 Ethernet and Gigabit Ethernet are completely different. Ethernet is usually separated into two major groups: 10/100 Ethernet transmits 10 and 100 Mbps and Gigabit Ethernet transmits 1,000 Mbps.

10/100 Ethernet uses only four lines of the cable and two differential channels: one for receiving and one for transmitting. Both data rates require isolation in form of a transformer on the receiving and transmitting lines of both cable ends. This means that two transformers are usually in one package. 10 Mbps refers to IEEE 802.3i 10BASE-T using a Manchester-encoded signal. 100 Mbps refers to IEEE 802.3u 100BASE-TX using an MLT3 signaling.

Gigabit Ethernet is completely different on the physical layer. All eight lines of cable are used for four differential channels and all are used bidirectionally at the same time. The need for isolation and transformers is similar to 10/100 Ethernet: each pair requires one transformer. In total, four transformers are required at each cable end. As for 10/100 Ethernet, there are also integrated transformers available. Integrated transformers for Gigabit Ethernet contain four transformers, so they are usually larger than transformers for 10/100 Ethernet. In space-critical applications, it can be possible to use two 10/100-Ethernet transformers for Gigabit Ethernet. The term Gigabit Ethernet or 1,000-Mbps Ethernet refers to 802.3ab 1000BASE-T, which uses PAM5 for signaling on the cable.

PoE for 10/100 Ethernet

Discussed above is how PoE is implemented in Gigabit Ethernet using all four pairs. The PD has to use all pairs to work with PSE alternative A and B. Ethernet with 10/100 Mbps uses only two pairs, so the cable has two pairs left.

These two pairs, pins 7/8 and 4/5 of an RJ45 connector, are often used only for PoE. The drawback is that a cable with eight lines is required. If for any reason a four-line cable is being used, the power has to be injected into the data pairs symmetrically into the transformers. This method is then the same as it is for Gigabit Ethernet.

Table 1. IEEE 802.3af power-up stages at PD

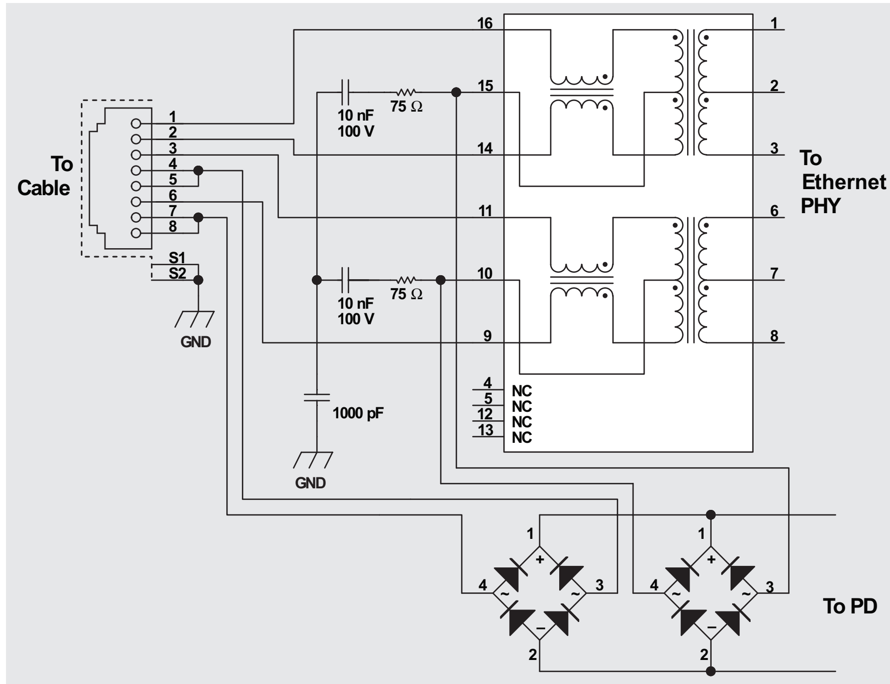
Stage	Comments	Voltage (V)
Detection	Sensing the signature resistor	2.7 to 10.1
Classification	Sensing the power class (see Table 2)	14.5 to 20.5
Startup	Voltage for the PD to start	42
Operation	Normal supply-voltage range	36 to 57

Table 2. Power classes

Class	Classification Current (mA)	Power at PD (W)	Power from PSE (W)	Comments
0	0 to 4	0.44 to 12.94	15.4	
1	9 to 12	0.44 to 3.84	4	
2	17 to 20	3.84 to 6.49	7	
3	26 to 30	6.49 to 12.95	15.4	
4	36 to 44	12.95 to 25.5	30	The 802.3at standard requires a PD to implement Link Layer Discovery Protocol (LLDP) signaling on Layer 2. LLDP is typically implemented on the systems processor and not in the PD controller. The PSE doesn’t need to implement LLDP

Figure 3 shows the implementation of a PoE PD for 10/100 Ethernet. As for the Gigabit Ethernet implementation, all four lines go to the PD controller through a rectifier bridge. This circuit enables powering the device independent of the polarity. It will work when adding power to the data lines or on the spare lines.

Figure 3. PoE for 10/100 Ethernet



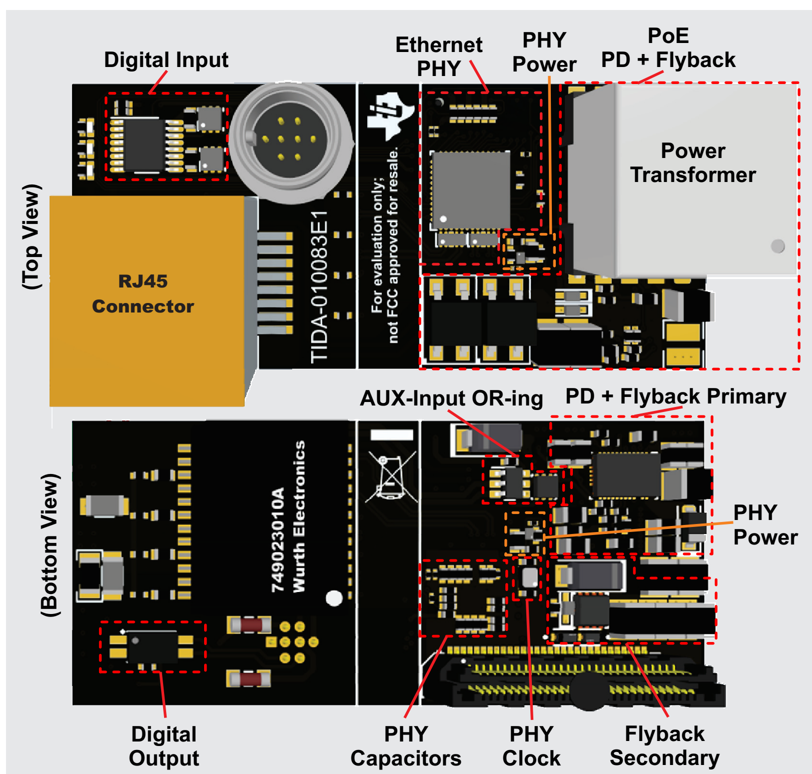
Implementing a small PoE solution for machine-vision cameras

As previously described, machine-vision cameras have a very-small form factor and must have low power consumption. Implementing PoE together with Gigabit Ethernet (GigE) in such a small form factor requires a high level of integration. To fit a printed circuit board (PCB) into a housing of 29 x 29 x 29 mm means that the PCB size has to be about 25 x 27 mm. This small size requires working in three dimensions: dividing the system into small subsystems that can be spread over multiple PCBs.

Figure 4 shows a complete solution that implements the power and data interface for applications like machine vision cameras and other space-constrained PoE implementations. The high-density isolated PoE and GigE reference design for machine-vision cameras and vision sensors consists of two small PCBs connected with a flex PCB in the middle. The PCB on the left contains the connectors, data transformer and digital input/output channels. A second PCB on the right contains the PoE solution and the necessary Gigabit Ethernet physical layer, including a clock and power supply on the right. In the middle, the flex PCB can be folded to fit into the housing.

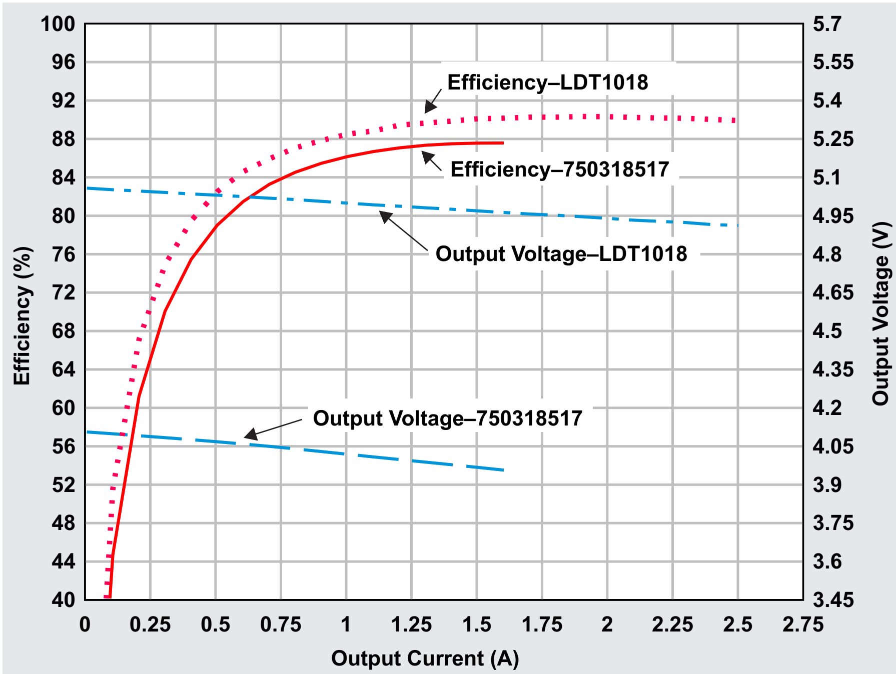
To keep the solution size small, the reference design uses an integrated IC (the TPS23758) containing all of the features of a separate PD controller, flyback controller and field-effect transistor (FET). Primary-side feedback negates the need for opto-coupler feedback as well as a secondary reference such as the TL431. This makes the design smaller and more reliable, and makes the voltage regulation faster to respond to current steps.

Figure 4. High-density reference design* for isolated-PoE and GigE machine-vision cameras and sensors



*Planned availability for TIDA-010083E1 reference design is November, 2019.

Figure 5. Efficiency plot for a PoE solution with the TPS23758 and different transformers



Power dissipation is critical in this type of application, making the replacement of the rectification diode on the secondary side a factor. Together with primary-side feedback, a diode rectification shows a current- and temperature-dependent voltage drop. In most applications this is not critical, but when the flyback is designed for 5 V and should directly supply a power-management IC (PMIC) with a 5.5-V maximum input voltage, voltage overshoot at low currents can cause trouble.

Both problems (the temperature and current depended voltage drop, as well as the power dissipation) can be solved by replacing the diode with a FET and applying additional winding on the transformer to control the FET. This synchronous rectification forces the regulator to stay in continuous conduction mode even at low loads, so the output voltage remains at the same voltage even at low load currents. Because the FET has much lower conduction losses than a diode, the power dissipation is reduced. The current- and temperature-dependent voltage drop is significantly reduced compared to the diode, which makes it suitable to directly power a 5-V PMIC.

Figure 5 shows the efficiency and output voltage of a TPS23758 with two different transformers. One transformer is designed for up to 7 W at 4 V, whereas another is designed for a 13-W, 5-V output.

Conclusion

PoE is a simple and effective way to combine power and high-speed data connection in one cable. There are important differences between 10/100 Ethernet and Gigabit Ethernet when it comes to implementing PoE. To distinguish between a PoE-capable device and a non-PoE device, the detection has to be implemented correctly. Signaling the power need to a PSE classification is necessary.

An example implementation with a very small footprint can be implemented as was shown in Figure 4. That PoE interface can be used for either 7-W or 13-W solutions with a very high efficiency at around 90% as shown in Figure 5.

References

1. VDMA Key Technology for Automation Solutions Machine Vision 2017/18.
2. Camera Sizes: the Smaller, the Finer.
3. LED-Lighting Control Reference Design for Machine Vision, Texas Instruments Reference Design (TIDA-01081).
4. Würth WE-RJ45 RJ45 LAN transformer.
5. TPS2388 PSE controller data sheet.

Related Web sites

Product information:

TI PoE solutions

TPS23758 (Check this product folder online for availability of TIDA-010083E1 reference design.)

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