SŁAWOMIR CHMIELARZ
TOMASZ MOLENDA
Institute of Innovative Technologies EMAG

Modern technologies of galvanic separation of digital signals and their possible applications in intrinsically safe devices

The article presents the reasons why the approach to separation has changed. Based on the solutions by Analog Devices and Texas Instruments, state-of-the-art technologies of galvanic separation of digital signals were presented. The authors described inductive coupling in the iCoupler technology and capacitive coupling in the ISO technology. Finally they discussed possible future applications of this kind of separation in intrinsically safe devices.

key words: optoelectronics, intrinsic safety of devices, galvanic separation.

1. INTRODUCTION

The use of separation had always been quite burdensome for developers. Yet, it was necessary due to different reasons [6]. Slower communication, high energy consumption and significantly big space occupied on the printed circuit board were the chief difficulties associated with separation. Therefore separation was simply unpractical in many cases.

An important date for the developers was the invention of modern optocouplers about 45 years ago. The isolation provided by optocouplers allowed to apply feedback in power supply control circuits, to break the ground loop in communication and to control power transistors from the positive side of power supply, and to make current control circuits.

In 1970s there was an increase in the production of optoelectronic devices. This had a considerable impact on the development of communication standards, such as RS-232 and RS-485, as well as industrial standards, including current loops 4-20 mA, DeviceNet and Profibus. The parameters and restrictions concerning optoelectronic elements used for separation purposes had a strong impact on many characteristics of the mentioned communication standards.

In 1980s and 1990s there was continuous progress in separation technology and in 2000 the first of the new separation integrated circuits was launched. These new elements were based on inductive coupling by transformers included in the integrated circuits, GMR (Giant magneto-resistive) materials and then by differential capacitive coupling.

The new technologies are able to work at much higher transmission speed and much lower energy levels than older solutions – optocouplers. Still, the standards remained unchanged and many possibilities of the new devices, such as high speed, were not fully used because the existing standard interfaces do not need them.

Digital separators are manufactured with the use of standard packages and technological manufacturing processes typical of integrated circuits. Thanks to that it is possible to have a simplified extension of functionalities contained in the separators of encoding- and decoding circuits and these functionalities are compatible with typical digital systems.

Low energy use, support of low voltage and a high integration level became the main constructional advantages of non-optic separators. This innovation allows to separate much higher speed values or use much less energy and enables to support the most demanding new interface standards.

Currently the use of energy in digital separators, though much lower than in optocouplers, has to be lower by two-three orders of magnitude so that they could be implemented in new applications [2].

Due to the above mentioned reasons, separation has been used so far for interfaces which transfer data at long distances but with moderate speed. High-efficiency separation, provided by integrated digital separators, allows to separate, simply and economically, fast and typical local interfaces, e.g. I2C, SPI, USB, I2S, SDIO. Separation circuits have separation sides which are supplied independently of each other with the voltages of 5 V or 3.3 V as well as the resulting logic states. Thus an extra advantage is the possibility to conduct the voltage conversion of logic levels.

2. COMPARISON OF SEPARATION TECHNOLOGIES

A progressive feature in separation elements is the connection of advantages of a data encoding system and the efficiency of a medium used to transfer these data. Both factors impact the energy consumption. The given type of separation is performed in the given technology. If this separation is applied along with the resulting medium, the given encoding system has an impact on the energy consumption.

The encoding and decoding systems can be divided into the following categories:

- encoding and decoding of edges,
- encoding and decoding of a level.

A system based on level-encoding must send energy all the time through the separation barrier in order to maintain the dominating output state. While in order to represent a recessive output state, no energy is transmitted through the barrier.

In optocouplers the energy transfer is carried out with the use of light, which has low efficiency with respect to direct generation of electric or magnetic fields and low detection efficiency in the receiving element. Optocouplers based on simple transistors or a PIN diode must consume a lot of energy when they produce light in order to maintain proper voltage/current parameters at the output. However, the receiver consumes too little energy to receive the signal. This is illustrated in Table 1 – the optocoupler which uses a PIN diode/phototransistor has high input current and low output current.

Table 1.

Comparison of power consumption by a single channel of different types of separation at Vdd = 3.3 V and the speed of 100 kbps [2]

Technology	Input current [mA]	Output current [mA]
High-speed digital optocoupler	2.5	8.5
High-speed optocoupler which uses a PIN diode/phototransistor	8	1.2
Digital separator with capacitive coupling	1.25	1
Digital separator with inductive coupling	0.5	0.23
Digital separator with inductive coupling of very low power	0.01	0.01

Faster digital optocouplers are characterized by reduced volume of light which is necessary to maintain the given state due to the active gain added to the receiver. Thanks to that the average current required by the diodes is smaller but the receivers have relatively big quiescent current, so the energy consumption is not significantly reduced but only transferred to the side of the receiver. Reducing the demanded power requires to increase the efficiency of the LED element and the receiver, or to change the encoding method. This is the progress basis in the development of the optocouplers technology [2].

There are some state-of-the-art digital separation solutions available on the market.

An example of using capacitive coupling is the ISO family of circuits by Texas Instruments, while inductive coupling – *i*Coupler circuits by Analog Devices.

These two solutions are similar to each other and they have significant advantages over optocouplers that have been used so far, in terms of miniaturization, transmission speed, consumed energy, and operation reliability [5].

Both inductive coupling applied by Analog Devices and capacitive coupling used by Texas Instruments do not transfer the direct component of the signal. In both cases it was necessary to use circuits which encode the information about the edges direction or about the logic state of the transferred signal on the primary side as the changes of current for inductive coupling or voltage changes for capacitive coupling. In addition, it was necessary to use proper systems which, on this basis, reconstruct the input signal on the secondary side

As it was not possible to transfer the direct component, capacitive or inductive coupling were used less frequently for the separation of bi-stable signals. For this purpose optical coupling was used.

3. CAPACITIVE COUPLING IN THE ISO TECHNOLOGY

The Texas Instruments ISO family make use of capacitive coupling. In this solution a single data channel is composed of two parallel channels: a fast (AC) channel with a bandwidth from 100 kbps to 150 Mbps and a slow channel from DC to 100 kbps. The structure of a single channel of a capacitive separator can be seen in Fig. 1.

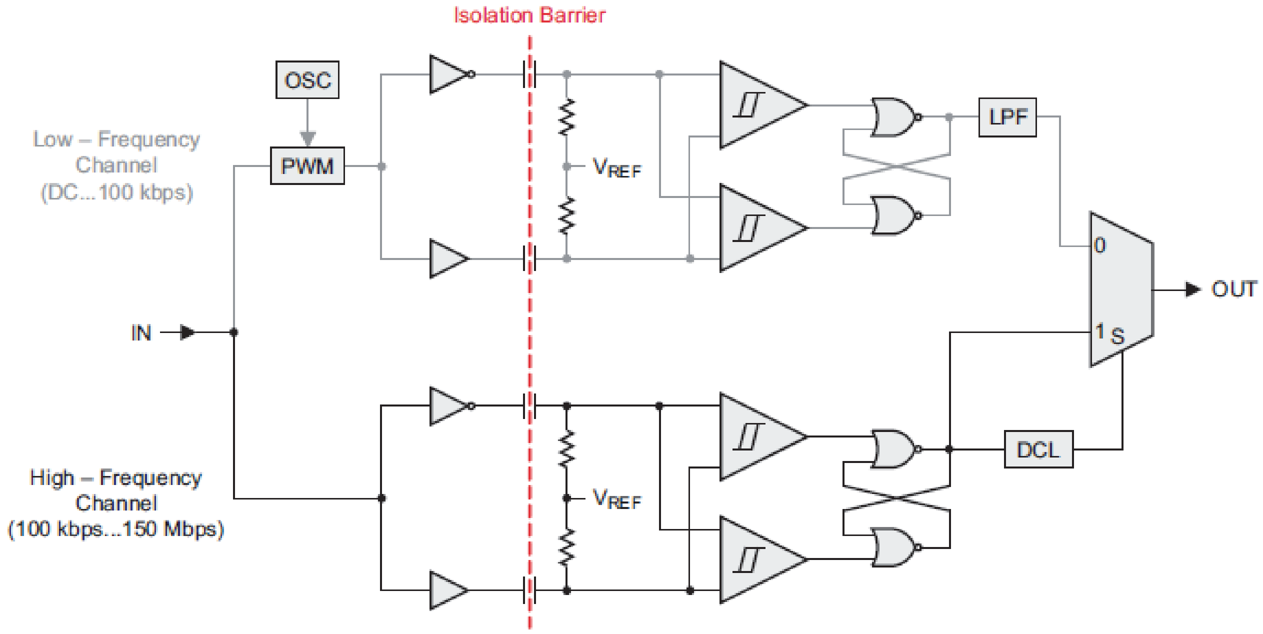

Fig. 1. Structure of a single channel of a capacitive separator [9]

3.1. Channel description for fast-changing signals (AC)

The incoming signal enters the AC channel directly and simultaneously to two buffers: an inverting buffer and a non-inverting one. At the output of one buffer the signal has a straight form, while at the output of the other – a negative one (Fig. 1). The outputs of the buffers are connected by RC differentiators (capacity is a series-type separation) to the inputs of two comparators which generate short pulses on the output dependant on the input signal edge direction. These pulses are generated from the opposite phase transient states on the outputs of differential circuits. As long as the voltage at the non-inverting input of the comparator is higher than that at the inverting input, the comparator output has a high state. The outputs of the comparators are connected to proper SET and RESET inputs of the RS trigger circuit made with the use of NOR gates. The RS trigger circuit is an inverting device, thus a high (active) state at the C input causes a high state at the /D output. Similarly, a high state at the /C input causes a high state at the D output. As impulses at the outputs of the comparators have very short duration it is possible to have a low state at both inputs of the trigger circuit. In such a situation, the trigger circuit maintains the previous state at its outputs. The signal at the /D output of the trigger circuit has the same phase and shape as the input signal of the channel. The diagram and time waveforms in particular points of the channel for fast-changing signals are presented in Fig. 2.

There is a decision circuit connected to the output of the AC channel trigger circuit. The decision circuit has a form of a watchdog which measures time between the signal switches. If the duration between two successive transients exceeds the length of the maximum time window, which occurs when a slow-changing signal is sent, the output multiplexer is switched from the AC fast-changing channel to the DC slow-changing channel.

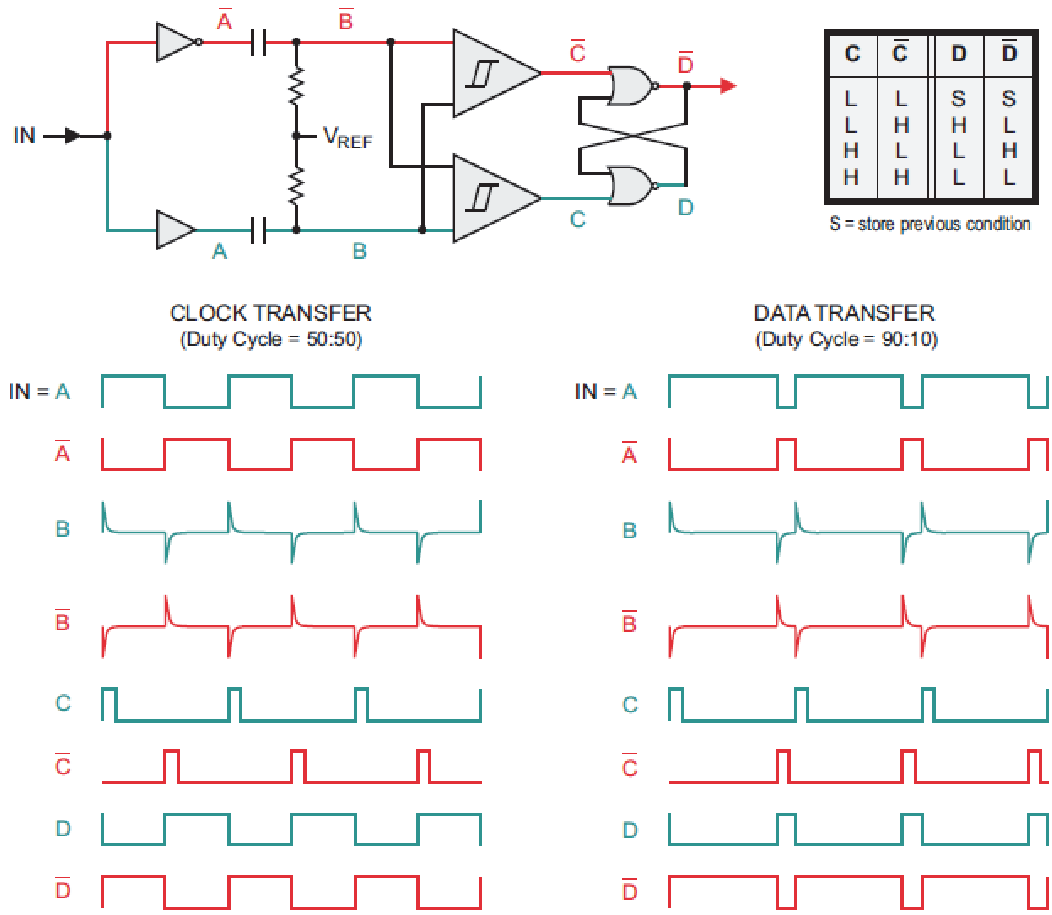

Fig. 2. Diagram and time waveforms in particular points of the channel for fast-changing signals [9]

3.2. Channel description for slow-changing signals

In order to pass slow-changing signals through capacitive separation in the slow-changing channel, the input signal is used to modulate the pulse width (PWM) of the internal generator. The modulated signal is passed through the same circuit as in the AC channel, however, a low-pass RC filter is installed at the RS trigger circuit output to remove the high-frequency carrier component. The carrier frequency and the operation of the modulator were adopted in such a way that when there is a high or a low state at the input of the channel, the duty cycle at the modulator output is 90% and 10% respectively. Figure 3 features the diagram and time waveforms in particular points of the channel for slow-changing signals.

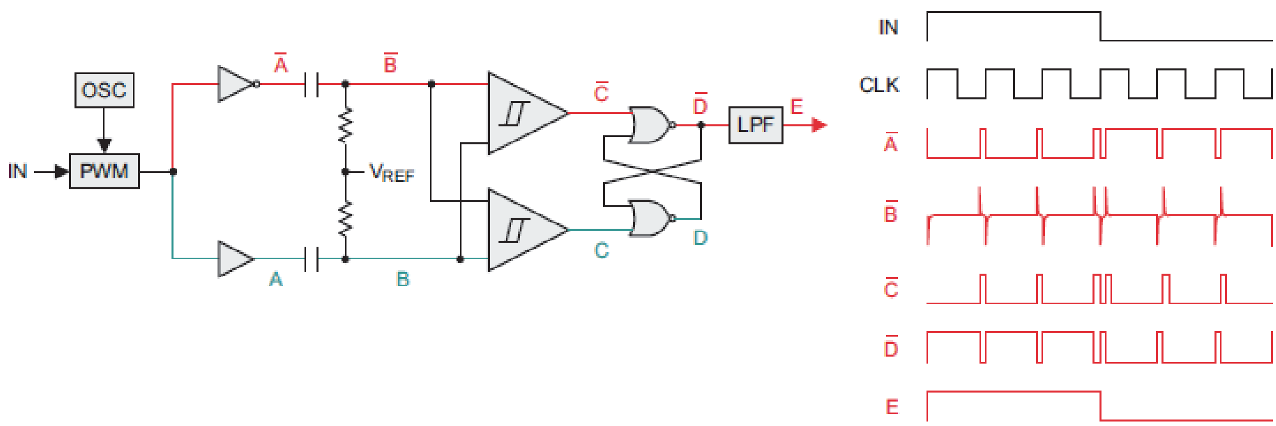

Fig. 3. Diagram and time waveforms in particular points of the channel for slow-changing signals [9]

The difference in the channels operation lies in the fact that the high-frequency carrier component of the low-speed channel /D is filtered through the RC low-pass filter before this signal is carried to the output multiplexer (Fig. 3).

Texas Instruments offer many versions of products that use the *ISO* separation technology. They differ in terms of the number of channels (1, 2, 3, and 4) and transmission direction combinations. Thanks to these features their application range can cover many commonly used digital interfaces.All *ISO* circuits make use of the CMOS logic with 3 V / 5 V single power supply. The nominal voltage range is between 3.3 V and 5 V to supply both separated sides and it is admissible to have any combination of these values. While using *ISO* digital separators one has to take into account that they are not in compliance with the specifications of any standard interface. Their only objective is to provide separation for 3 V / 5 V digital signal lines. In the separation of interfaces such as SPI, RS-232 and RS-485, a separator is used between the controller system (e.g. microcontroller or UART) and the transceiver of the bus or other circuit, independently of the interface standard as such.

Apart from universal, independent circuits, Texas Instruments use the *ISO* separation technology in RS-485 transceivers by means of integrating an RS-485 transceiver and an ISO separation system in one integrated circuit. Thanks to this solution it is possible to separate the RS-485 transmission with a minimum number of elements, just by applying a bus transceiver with inner separation and with separate power supply to the controller and bus sides [9].

4. INDUCTIVE COUPLING IN THE *i*COUPLER TECHNOLOGY

Digital separators by *i*Coupler Analog Devices make use of micro-transformers as coupling elements. These micro-transformers are integrated in an integrated circuit for data transmission by means of a high-quality polyamide isolation barrier.

The *i*Coupler separators make use of two basic data transmission methods: unipolar and differential data transmission. The choice of one of these methods is a compromise that enables to optimize the characteristics of an element.

In the case of unipolar communication one of the transformer terminals of the primary side is connected to the reference potential. The changes in the logic state of the input signal are encoded by means of pulses which always have positive polarization with respect to the reference potential on the transmitter side. This method is also called “one pulse-two pulses” as the rising edge of the input signal is encoded by two consecutive pulses, while the falling edge by means of a single pulse. The receiver on the other side of the isolation barrier receives pulses and decides whether one or two pulses were sent. On this basis the receiver recreates the rising and falling edges on the secondary side.

The differential method of data transmission makes use of a transformer in a real differential manner. In this solution a single pulse is sent at each edge of the input signal but the polarization of the pulse depends on the character of the edge, i.e. whether it is rising or falling. The receiver is fully differential too and updates the output state based on the pulse polarization.

One of the main advantages of the unipolar solution is lower energy consumption at low speed of data transmission. This results from the fact that a differential receiver needs bigger polarization current than a CMOS gate with a Schmitt trigger input which is used in the unipolar solution. However, the differential solution has lower energy consumption at higher transmission speed. This is due to two reasons: smaller drive level and smaller number of pulses. The drive level of the transformer can be reduced because the receiver has to determine only the polarization instead of determining the presence of a single or double pulse. On average, the unipolar solution needs 1.5 pulses per edge, while the differential one – one pulse per edge (reduction by 33%).

The reduced drive level and a smaller number of pulses reduce the radiated emission. The emission is generated by the conductive tracks of printed circuit boards while current pulses are received from the power supply source. As the circuits which make use of the differential solution send fewer pulses and the energy of each pulse is smaller, the radiated emission is significantly lower.

The circuits with differential data transmission have two more advantages over the unipolar ones, i.e. shorter propagation time and immunity to disturbances. Single and double pulses in unipolar circuits have to be generated in a proper time dependency and the receiver has to analyze them within a certain time slot. These requirements force time restrictions on encoding and decoding which, in turn, causes the delay of signal propagation in the separator. This limits the total throughput that the element can achieve.

The differential solution has fewer limitations because a single pulse is always used, propagation delays are smaller and the throughput is bigger.

A differential receiver is reliable in detecting differential signals sent by the transmitter. This eliminates unwanted common mode transient disturbances which are typical of circuits with separation and, in turn, significantly increases the immunity to short-term common mode transient disturbances . In addition, a differential receiver is less vulnerable to power supply disturbances which improves the circuits immunity to disturbances too. The LED diodes in optocouplers are, by nature, supplied in a unipolar manner which results in lower CTMI immunity characteristic of optocouplers. Differential data transmission provides extra advantages to *i*Coupler separators over optocouplers. Both encoding methods are presented in Fig. 4.

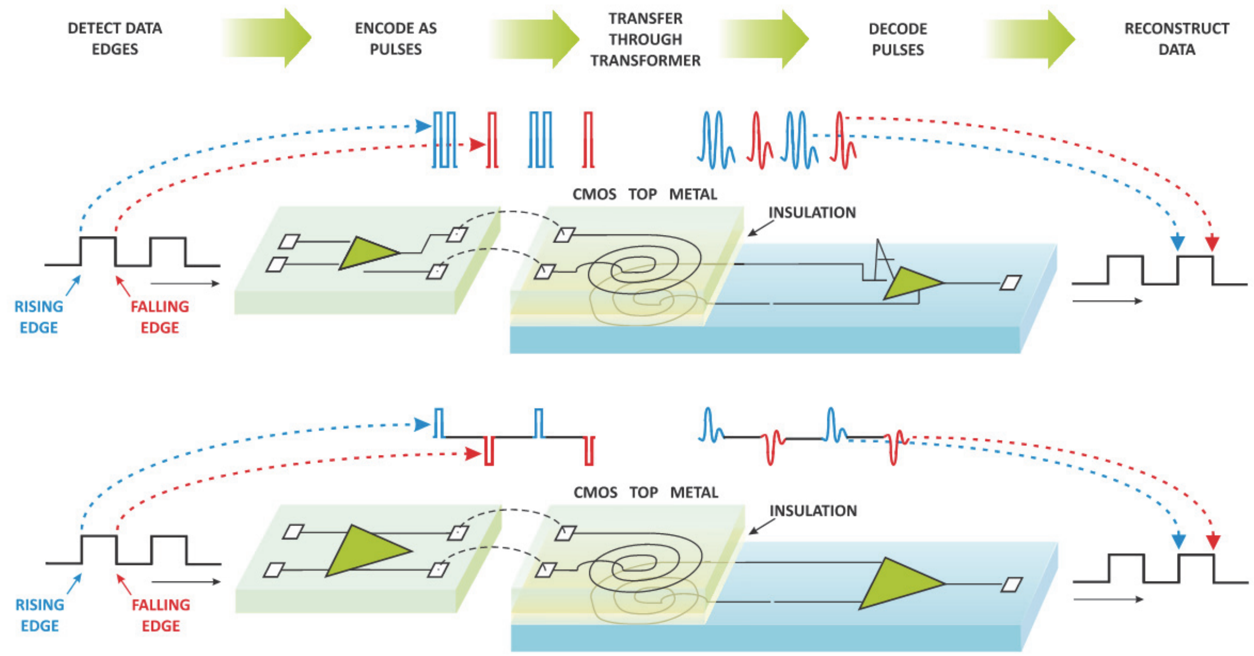

Fig. 4. Encoding by means of the number of pulses and the polarization of pulses

The data transmission methodology is one of the methods to use at the optimization of the digital separators efficiency. If we have an element with a real differencial coupling based on the *i*Coupler technology, it is possible to have much flexibility in this range, and such flexibility is usually impossible for solutions based on optocouplers or capacitive coupling [3].

Each data encoding method has different characteristics and works better in certain applications. The characteristics of encoding based on the number of pulses and differential encoding are demonstrated in Table 2 [1].

Table 2.

Comparison of characteristics of different encoding methods in *i*Coupler circuits [1]

Encoding based on the number of pulses	Encoding based on (differential) polarization of edges
– Very low consumption of energy at low speed of transferred data	– Lower consumption of energy at high frequencies – Higher consumption of energy at low frequencies
– Short propagation time	– Shorter propagation time
– High speed of transmission	– Higher speed of transmission
– High immunity to common mode disturbances	– Better immunity to disturbances
	– Smaller number of sent pulses
	– Lower emission
– Coupling independent of the isolation thickness	

Detailed description of encoding based on a number of pulses

In order to achieve the data integrity and immunity to disturbances, the iCoupler technology makes use of glitch filters which reduce harmful impact of noise at each input of the signal line.

In order to be transferred through the isolation barrier in digital iCoupler separators, the data are encoded by means of short one-nanosecond pulses. Two consecutive pulses indicate a leading edge, while a single pulse – a falling edge. The circuit of the receiver decodes these pulses and recreates the rising and falling edges on the secondary side.

This type of narrow-pulse encoding in the CMOS standard uses less energy (by one order of magnitude) than optocouplers which use power continuously when the LED diode is on. All digital *i*Coupler separators use refresh circuits which resend the last data pulse if there are no data within 1 μs. Thanks to this solution, there is DC correctness at start-up and data errors are corrected within 1 μs. In addition, the *i*Coupler products have the fail-safe feature which ensures that the output is in a safe default state if the power on the input side fails. The watchdog timer on the secondary side provides a safe default state on the output side if there are no new data or refreshing pulses within 3 μs. Each circuit has its own default output state, either fixed or selectable. This feature protects downstream circuits against erroneous states which could cause damages [4]. The above described encoding method based on the number of pulses is illustrated in Fig. 5 [5].

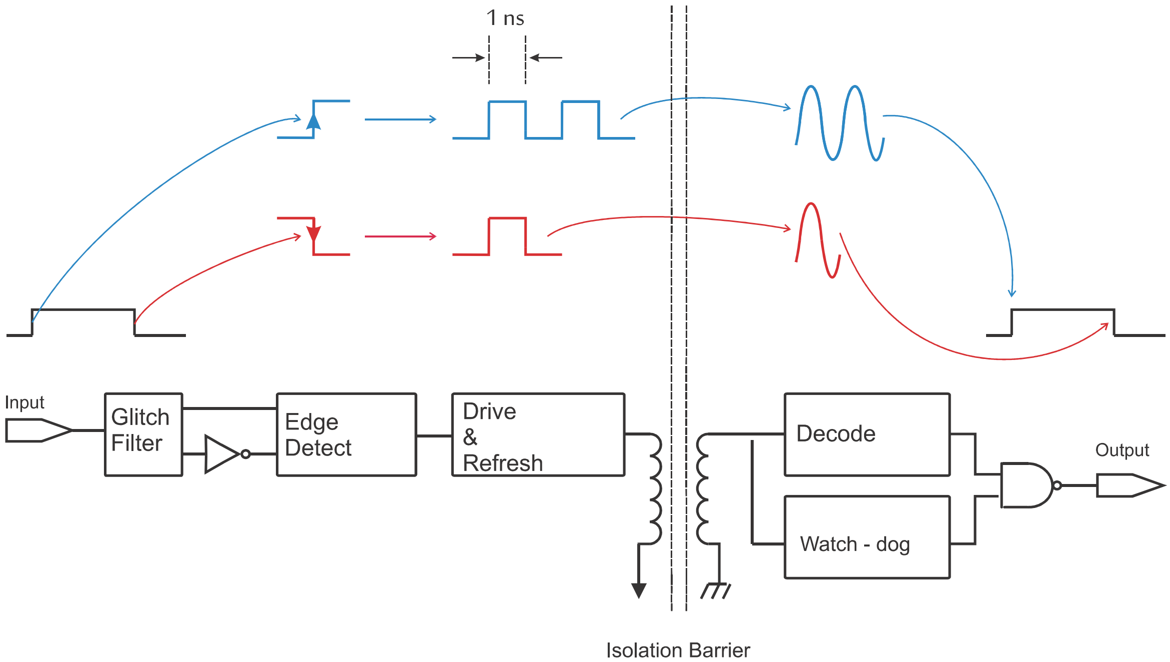

Fig. 5. Encoding by means of the number of pulses

In many digital capacitive-coupling separators the operaton method is very similar to that of an optocoupler. In these elements, in order to send a signal through a pair of differential condensers, the high frequency of the generator is applied. Similarly to the diodes of optocouplers, the generator consumes energy when it is on sending an active state and does not consume energy when it is off sending a recessive state. The receiver has an active amplifier which uses energy to provide polarization current, independently of the received state. As it can be seen in Table 1, due to high coupling efficiency of the condensers, the total consumption of power is much lower than in the case of an optocoupler.

It is important to note that the power level in digital separators will be similar if inductive coupling is used instead of capacitive. In this case, first of all, the encoding method is important. The method determines the minimum power level, particularly at low speed values of data transmission.

Digital separators based on the technology of *i*Coupler Analog Devices, such as ADuM140x, apply the encoding method which uses the number of pulses.

These pulses are reliable and allow to achieve a good signal-noise ratio. However, they are very short (only 1 nS of time duration). Thus the energy per 1 pulse is very small. This solution works well when data lines do not change the state. Then the output state is maintained in the trigger circuit and hardly any energy is used. This means that the energy consumption is simply the energy provided to the pulse streams, integrated in time and extended by the energy indispensable to have current polarization. It is important to note that this encoding method ensures the reduction in energy consumption but is not related to any particular data transmission medium. This method can be applied in capacitive circuits or even optical circuits.

The pulse-encoding method as such is not an ideal solution to achieve low energy consumption. Its major drawback is that if there are no changes of the logic state at the input, no data are sent to the output. This means that if there is a difference of the direct component level, resulting from the start-up sequence, the logic output state may be not in compliance with the input state. In ADuM140x circuits this problem was solved by using a watchdog on the input side. The watchdog resends the input state if no activity over 1 μS has been detected in it. Such a solution brings about certain results, i.e. this encoding method does not allow to reduce energy consumption when the data transmission speed is below 1 Mbps. This element works efficiently at the transmission speed of at least 1 Mbps. Thus the energy consumption does not drop at lower speed values of data transmission. In spite of that, the pulse-encoding method ensures lower average energy use than the systems which are based on a constant level (see Table 1).

In the family of separators ADuM140x the encoding method based on pulses was optimized for high data transmission speed, not strictly for the lowest energy consumption. This kind of encoding has a much bigger potential in terms of further reduction of power, especially in the transmission speed range from DC to 1 Mbps. The majority of separation circuits are within this range of transmission speed, particularly those for which low energy consumption is a significant issue.

The following innovations were implemented in four-channel (ADuM144x) and two-channel (ADuM124x) product families based on the *i*Coupler technology:

1. They were made in the CMOS lower voltage technology;
2. All polarization circuits were verified and, wherever it was possible, the polarization was minimized or eliminated;
3. Circuit refreshing frequency was reduced from 1 MHz to 17 kHz;
4. Refreshing circuit can be switched off to ensure the lowest possible energy consumption.

Figure 6 features the consumption of current depending on frequency, with respect to the ADuM140x separators [2].

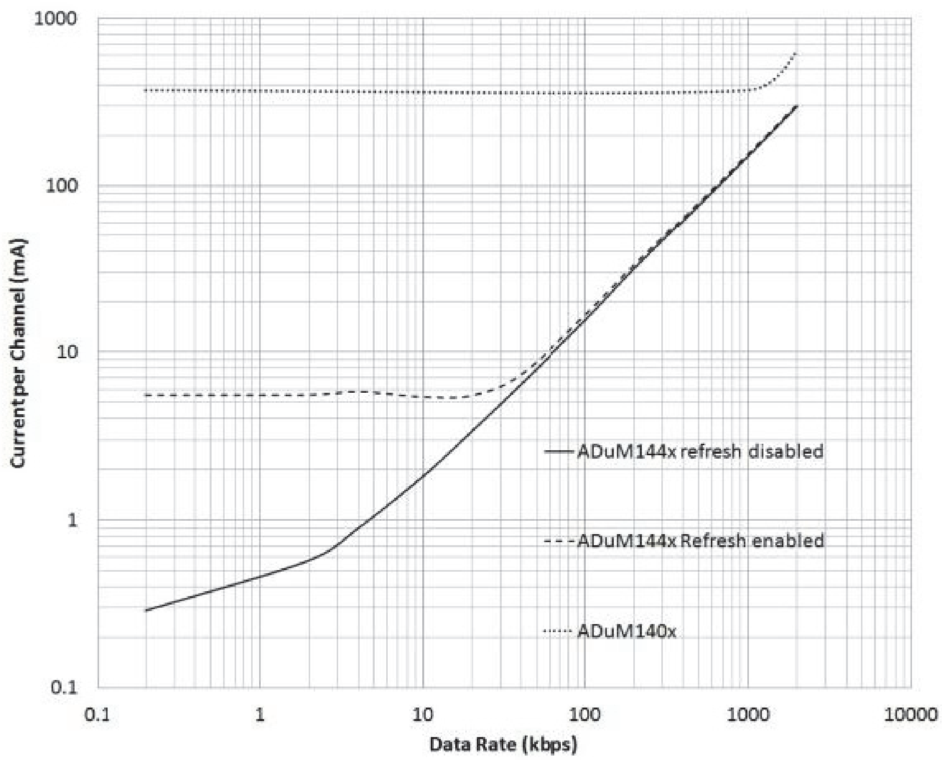

Fig. 6. Total current intake per one channel for ADuM144x and ADuM140x at Vdd = 3.3 V [2]

The curves of the characteristics caused by the refreshment can be easily seen for 1 Mbps for the ADuM140x separators and for 17 kbps for the ADuM144x separators when the refreshment function is on. ADuM144x have a typical current intake per channel, 65 times smaller for 1 kbps and about 1,000 times smaller if the refreshment is completely disabled. [2].

5. CONCLUSIONS

The integration of all processing, forming, encoding and decoding circuits in one element is a significant difference in comparison with older solutions that used capacitive and inductive coupling to send bi-stable signals.

In the solutions that have been used so far, the above circuits were made on the basis of discrete elements, which were associated with higher fallibility, worse functional parameters, more surface needed for a print circuit board, higher energy consumption, and higher costs.

However, in the case of intrinsically safe devices, the solutions based on discrete elements allow to apply a separating element (transformer or condenser) with proper parameters and structure in compliance with PN-EN 60079-11 [7]. Then it is possible to use such separation to separate intrinsically safe circuits from non-intrinsically safe ones. The requirements for condensers are included in clause 8.6.1 of the standard, and for transformers – clause 8.3.

An optimal solution for intrinsically safe devices would be to integrate in an integrated element only processing, forming, encoding and decoding circuits, while the separating element as such would remain a discrete element. Then the separation would be made of signal-forming integrated circuits on both sides of the separation. While the separating elements, which are indestructive (as understood by the standard), would be placed between the integrated circuits.

The discussed encoding methods can be implemented in fibre-optic separation too. If an optical fibre is placed in a zone with explosion hazards, it is necessary to meet the requirements of the PN-EN 60079-28 standard [8]. Such integrated circuits could be cheaper to develop and manufacture. Additionally, they would be much simpler from the technological point of view, i.e. they would not contain separating elements which are troublesome to make in the structure of an integrated circuit. The parameters of such separation would certainly be lower than those of an integrated circuit. Still, the advantages, such as reduced energy consumption and minimized separation circuit, would be significant. Most probably, however, the market of solutions for intrinsically safe devices is too small to make the development of such circuits profitable enough for manufacturers.

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The article was reviewed by two independent reviewers.