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PROCESS SAFETY PROGRESS

ORIGINAL ARTICLE

Verification of intrinsic safety on instrumentation loop

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Abstract

Intrinsic safety is one of the explosion protection techniques implemented in an industry where a flammable substance is present. It is a technique that reduces the electrical energy level at the hazardous area below the ignition curve so that it is not sufficient to initiate an explosion. In addition to limiting the energy to the field, the energy stored in the circuit and thermal ignition due to hot surfaces in hazardous areas must also be considered. Intrinsically safe is the preferred explosion protection method for instrumentation and control signals as it allows live maintenance, the use of an uncertified simple apparatus, and is applicable to all Zones. All intrinsically safe circuits must carry out a safety assessment and verify their compliance with intrinsic safety before implementation to avoid explosion. The verification process could be complex for mixed circuits and non-simple intrinsically safe systems; moreover, there has been much confusion for many years until the 4th Edition of the installation standard, IEC 60079-14, provided a clearer picture. This paper carries out an intrinsic safety verification assessment on a mixed circuit involving surge protection devices according to IEC and NEC standards. It also highlights the common mistake made by system designers when verifying the safety parameters.

KEYWORDS

entity parameter, intrinsic safety, safety assessment, safety parameter, safety verification, surge protection device

1 | INTRODUCTION

The intrinsically safe (IS or Ex i) concept was closely associated with mining explosions initially. As the widespread use of chemicals grew, especially in the petrochemical industry, the concept was widely adopted by the petrochemical industry. IS originated in the United Kingdom in 1913. On October 14, 1913, a severe explosion occurred that caused 439 miners to lose their lives in the Senghenydd Colliery, England. This incident is also known as the Senghenydd explosion in the United Kingdom. The official report from the England Home Office cited that the sparks that ignited the firedamp explosion were from the Leclanche Signaling Bell used by the miner. Further investigation by the Home Office and Durham University in 1915 and 1916 confirmed that the spark was due to the energy stored in the inductive coil of the bell. The stored energy could have been suppressed to a safe level by limiting the source voltage and restricting the energizing current with a resistor. This led to the evolution of intrinsic safety.[1]

Ex i is an explosion protection technique that lower the electrical energy level within the interconnecting devices and cables in the explosive atmosphere below the energy that could cause an ignition either by sparking or heating effect.[2] Any impact from an electrical spark, heat or hot surface in any part of the IS circuitry intended for use in hazardous (Ex) areas will not have sufficient energy to cause an explosion. Therefore, live maintenance and repair work can be carried out, and this work is allowed without a hot permit in the actual practice. For other methods of explosion protection, such as flameproof (Ex d), increased safety (Ex e), pressurization (Ex p), and others, it is required to shut down the power before maintenance and repair work is carried out. When an oil refinery or an offshore platform facility needs to shut down for maintenance, it will cost millions of dollars per day. Hence, for

TABLE 1 The IEC definition of the protection method and applicable zone of use[3]

Method of Protection	Ex code	Permitted in: Zone 0	Zone 1	Zone 2
Encapsulation	ma	√	√	√
	mb		√	√
Oil immersion	o		√	√
Powder filling	q		√	√
Pressurization	p		√	√
Flameproof	da	√	√	√
	db		√	√
	dc			√
Intrinsic safety	ia	√	√	√
	ib		√	√
	ic			√
Increased safety	e		√	√
Type of protection "n"	nA			√
	nR			√
	nC			√

instrumentation and control signal, Ex i is preferred compared to other explosion protection methods.

Since Ex i is an energy limiting method, all the apparatus used must be certified, except the simple apparatus (see the explanation in Section 2.1). These ensure that there is no sufficient stored energy, no ignition sparking, and heating or hot spot energy that could initiate an explosion. An Ex i certificate will be issued to an individual IS apparatus. All safety parameters will be specified on the certificate. Ex i is a system approach: not a single piece of equipment but the entire intrinsically safe circuit. Hence, when applying Ex i, "proof of intrinsic safety" is required to confirm the safety of the entire system using the entity parameters from the individual apparatus certificates that include the details of the cable specification and the simple apparatus used in the system.

Table 1 summarizes information on the various explosion protection techniques and their permitted zone of applications according to the IEC standard.

2 | LITERATURE REVIEW ON INTRINSIC SAFETY

Ex i is fundamentally a low-energy protection technique that works by restricting the available voltage (V), current (I), and power (P) to the field below the ignition energy level. It also considers the energy stored in the Ex area by the interconnecting cable and the field devices. In addition, it prevents the creation of any impermissible hot surfaces that could trigger an ignition from the electronic components used. The available energy levels for Ex i circuitry are small, but they are more than sufficient for the operation of most of the instrument and its control signals. The useable energy amount for intrinsic safety is taken from the ignition curves obtained experimentally using a "Spark Test Apparatus."[1,2] The curves are Resistive, Capacitive, and Inductive ignition curves, as shown in Figures 1–3. The curves are now published in the IEC/EN 60079-11.

The resistive ignition curve (Figure 1A) provides the maximum open-circuit voltage (Vo) value and the maximum short circuit current (Io) value (Figure 1B) from the IS interface or the supply source under normal and fault conditions to the hazardous area. The terms IS interface, IS isolator, or safety barrier refer to the same item and are used interchangeably. These values are below the ignition curve and insufficient to cause an explosion for different gas groups, as shown in Figure 1A. Any combination of the Vo and Io touching or above the curve could trigger an explosion. Any value below the curve will not have sufficient energy to ignite an explosion.

The capacitive ignition curve (Figure 2A) provides the total maximum equivalent external capacitance (Co) (Figure 2B) at the applied voltage that is allowed to be connected in the hazardous area for different gas groups, as shown in Figure 2A. The total equivalent external capacitance (Co) at the applied voltage should be below the curve so that the stored energy by that capacitance will not have sufficient energy to cause an explosion.

The inductive ignition curve (Figure 3A) provides the total maximum equivalent external inductance (Lo) (Figure 3B) at the applied voltage that is allowed to be connected in the hazardous area for different gas groups, as shown in Figure 3A. If the total equivalent external inductance (Lo) at the applied voltage is below the curve, the external inductance's stored energy will not have sufficient energy to ignite an explosion.

When designing an IS interface, the maximum output voltage (Vo), maximum short circuit current (Io), maximum connectable external capacitance (Co), and maximum connectable external inductance (Lo) can be derived from the ignition curves with an appropriate safety factor. The safety factor depends on the level of the protection circuit. The IEC 60079-11 defines three levels of protection for Ex i protection. They are summarized in Table 2. Only Ex ia is permitted to be used in Zone 0.

The relevant safety factors are:

- Level of protection Ex ia and Ex ib: safety factor 1.5 applied.
- Level of protection Ex ic: safety factor 1.0 applied.

There are many advantages in using IS protection; some of these advantages are summarized below:

- Explosions are prevented, not contained, and IS protection is permitted for use in Zone 0, 1, and 2. It is a much more cost-effective method. It does not require a bulky and heavy flameproof enclosure (Ex d), armored cable, and Ex d cable entry gland, especially in offshore and FPSO applications where space and weight are critical.

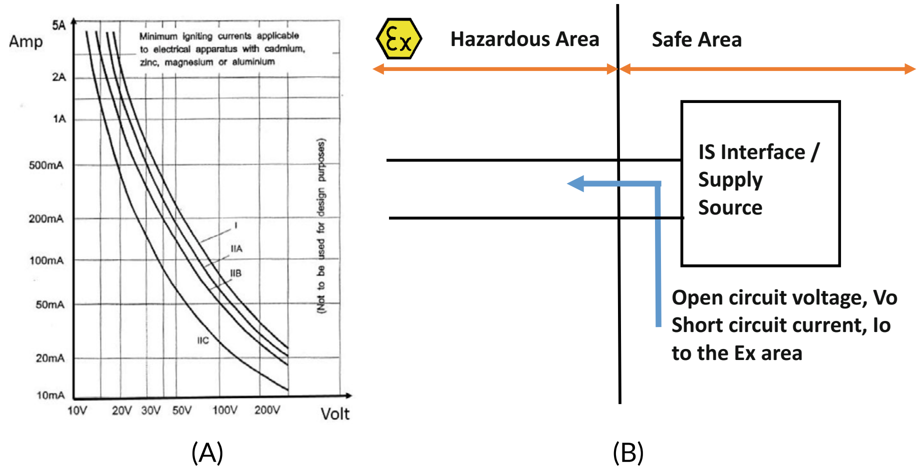


FIGURE 1 (A) Resistive ignition curve[2] (B) Open circuit voltage, Vo and short circuit current, Io from the supply source to the Ex area

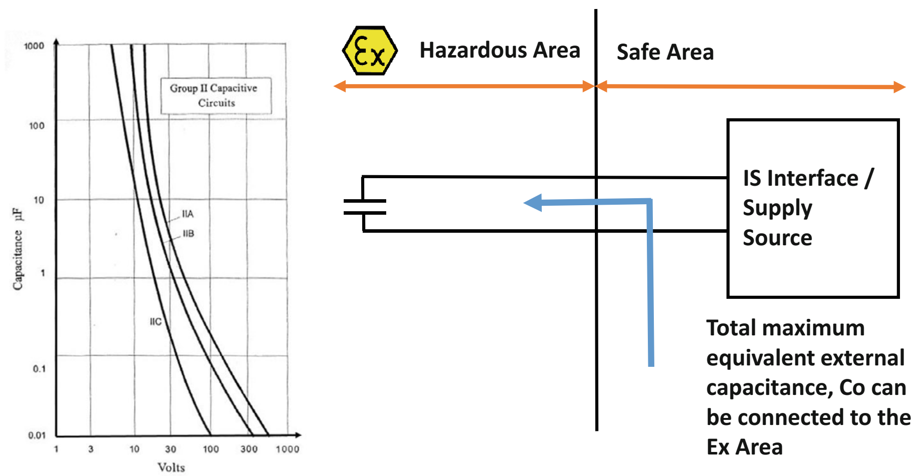


FIGURE 2 (A) Capacitive ignition curve[2] (B) Maximum equivalent external capacitance, Co allowed to connect to the supply source at the Ex area

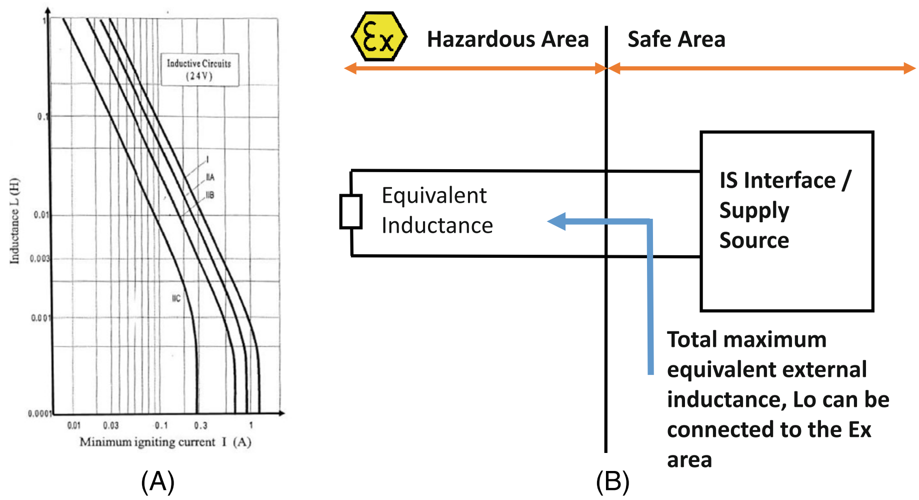


FIGURE 3 (A) Inductive ignition curve[2] (B) Maximum equivalent external inductance, Lo allowed to connect to the supply source at the Ex area

TABLE 2 Fault tolerance on Ex ia, Ex ib, and Ex ic[3]

Level of protection	Zone of use	Fault count
Ex ia	Zone 0	Safe with two countable faults
Ex ib	Zone 1	Safe with one countable fault
Ex ic	Zone 2	Safe with no countable faults, that is, safe in normal operation

- It allows live maintenance and modifications during operation without turning off the power supply or getting a hot permit to repair, thus lowering operating and maintenance costs.
- The use of an "Uncertified Simple Apparatus" is allowed without the need for further certification when connected through a safety barrier.

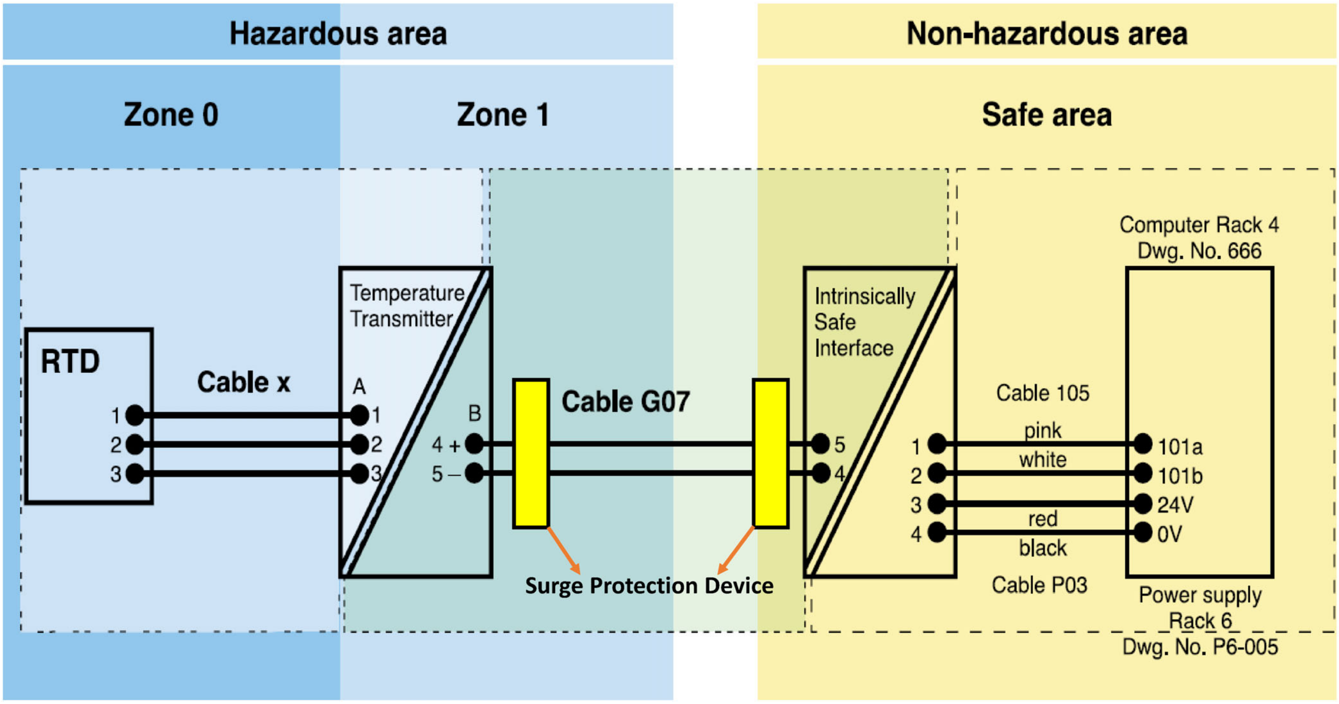


FIGURE 4 Typical Ex i loop, adopted from[7] with enhancement

TABLE 3 T4 classification for simple apparatus per IEC/EN 60079-14, section 16.4[9]

Total surface area of a simple apparatus (excluding lead wires)	P_o: Simple apparatus (ambient temperature at the point of installation)
<20 mm^2	$T_{surface}$ ≤ 275°C
≥20 mm^2 … ≤1000 mm^2	$T_{surface}$ ≤ 200°C
≥20 mm^2	Po ≤1.3 W at 40°C
	Po ≤1.25 W at 50°C
	Po ≤1.2 W at 60°C
	Po ≤1.1 W at 70°C
	Po ≤1.0 W at 80°C

- It creates a safe work environment as it deals with a low signal and no electrical shock.

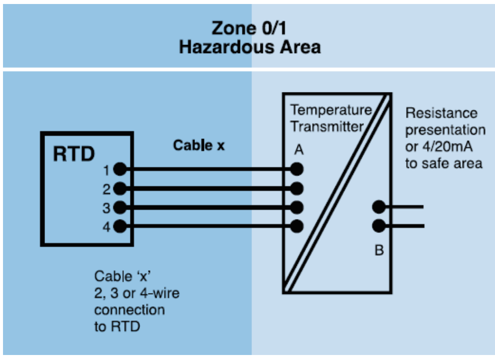
2.1 | Simple apparatus

According to IEC 60079-25: 2020 Edition 3,[4] a "Simple Apparatus" is a device that does not generate or store energy of more than 1.5 V, 100 mA, and 25 mW. Examples of simple apparatus are thermocouples and other passive components like mechanical switches, junction boxes, resistors (including PT100), and simple semiconductor devices.[5] There is some confusion about whether the voltage should be 1.5 or 1.2 V. The U.S. standard (NEC Article 500) still uses the old definition of 1.2 V, whereas the IEC uses 1.5 V. In practice, it makes very little difference.[5] In any case, the energy limitation for a simple apparatus applies to a single unit, as well as the combination of all the pieces of simple apparatus in a system. For example, using one or two thermocouples in a system may be permitted, but a combination of a large number used in a single, average temperature circuit might not meet this criterion.

With the introduction of an intrinsically safe technique, the uses of an "Uncertified Simple Apparatus" are allowed as defined by IEC 60079-25 in an Ex area without additional certification when the simple apparatus is connected to the field through a certified IS interface. However, the user must ensure that the simple apparatus meets the characteristics specified in IEC 60079-11 for energy storage and that the construction specifications conform to IEC 60079-11 Clause 6.2.1 and 6.3.13. Moreover, the user must determine the surface heating of the devices via the Po value (maximum output power from the power source/safety barrier) to assign them a temperature class. The simple apparatus is also required to pass the insulation test at 500 Vrms (one-minute duration) to be used in the Ex area.[6] Note: Although a simple apparatus does not have to be certified according to the standard, some manufacturers do get their product certified to increase the user's confidence level for those unfamiliar with the standard and marketing purposes. It is also not unusual for a simple apparatus that is used in significant quantities to be certified. When it is certified, it needs to be marked.

3 | METHODOLOGY: SAFETY EVALUATION PROCESS FOR AN INTRINSICALLY SAFE SYSTEM

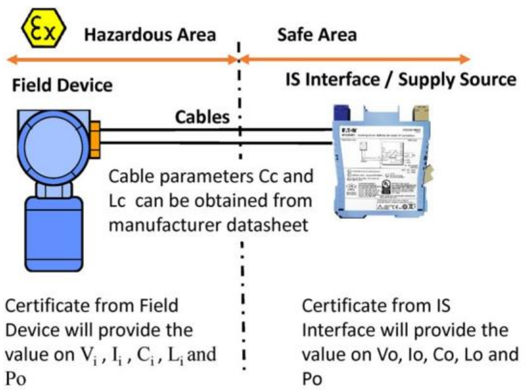
When verifying intrinsic safety, two critical questions need to be answered:



Key specification:
Temperature Transmitter Type: 365S from Pan Inc., Boston, USA
Classification: Ex ia IIC T4 by FUML No. 983065
Ambient Temperature, $T_{amb} = -40°C$to +80°C
Safety parameter at Terminals 'A'; Uo: 1.0 V; Io: 10 mA; Po: 2.5 mW; Co: 1000μF and Lo: 350 mH

RTD Type: 350L from Peter Pty, Sydney, Australia
Simple Apparatus to IEC 60079-11
Maximum operating temperature 450°C
The maximum measured temperature determines temperature classification.

FIGURE 5 Application of an Ex i field temperature transmitter. Adopted from Reference 7



Safety evaluation equations:

$$V_i \geq Vo \quad (1)$$
$$I_i \geq Io \quad (2)$$
$$Pi \geq Po \quad (3)$$
$$C_i + C_c \leq Co \quad (4)$$
$$L_i + L_c \leq Lo \quad (5)$$

Where
V_i = Max. permissible input voltage
I_i = Max. permissible input current
Pi = Max. permissible input power
C_i = Max internal field device capacitance
L_i = Max. internal field device inductance
Cc = Max. cable/line capacitance
Lc = Max. cable/line inductance
Vo = Max. output voltage
Io = Max. output current
Po = Max. output power
Co = Max. connectable external capacitance
Lo = Max. connectable external inductance

FIGURE 6 Safety parameters from different devices

Can ignitable sparks be generated? And can impermissibly hot surfaces be generated?

While the first point is obvious to anyone who knows the principle of intrinsic safety, the second point is often neglected when assessing a simple apparatus.

It is essential to recognize that where pieces of intrinsically safe apparatus are interconnected, the system's safety must be established. However, there are some examples of stand-alone apparatus for which the system approach is not relevant; for example, an IS mobile telephone and IS portable gas detectors are self-contained and not powered externally.

Figure 4 shows a typical Ex i system consisting of a field instrument (temperature transmitter) located in the hazardous area (Ex), surge protection devices (SPDs), interconnecting cables, and an intrinsically safe interface.[7] The safety of all Ex i systems depends on the integrity of every piece of equipment in the loop. For example, the safe application of the temperature transmitter (Tx), SPDs, and others, depends on the amount of energy supplied by the IS interface and the stored energy of each interconnected device. In fact, for Ex i, every piece of equipment in the system needs to be individually certified (except for the device classified as simple apparatus). A certificate will be issued to the individual piece of certified equipment. The certificate will state all the safety parameters like the maximum output voltage (Vo), maximum output short circuit current (Io), maximum connectable external capacitance (Co) and inductance (Lo); maximum permissible input voltage (V_i), maximum permissible input current (I_i), maximum internal field device capacitance (C_i), maximum internal field device inductance (L_i), maximum permissible input power (P_i) and maximum output power (Po). The user, operator or system designer will have to perform the safety validation and prove that the system is intrinsically safe.

From the physical aspect of intrinsic safety, the safety barrier (source) will determine the values of voltage (V), current (I), and power (P). The field device and the cable mainly determine inductance (L) and capacitance (C).

3.1 | IS verification process for simple apparatus

3.1.1 | Assessing spark ignition

Simple apparatus such as terminals, connectors, resistance temperature detectors (RTD/PT100), or thermocouples contain no or negligible lumped inductances (L_i) or capacitances (C_i). Therefore, they do not influence the energy of generated sparks.

3.1.2 | Assessment of thermal ignition

A simple apparatus needs to be assigned a temperature classification when it is intended for use in Ex area. The IEC 60079-14: 2013[8] standard allows a T6 temperature classification for components in which

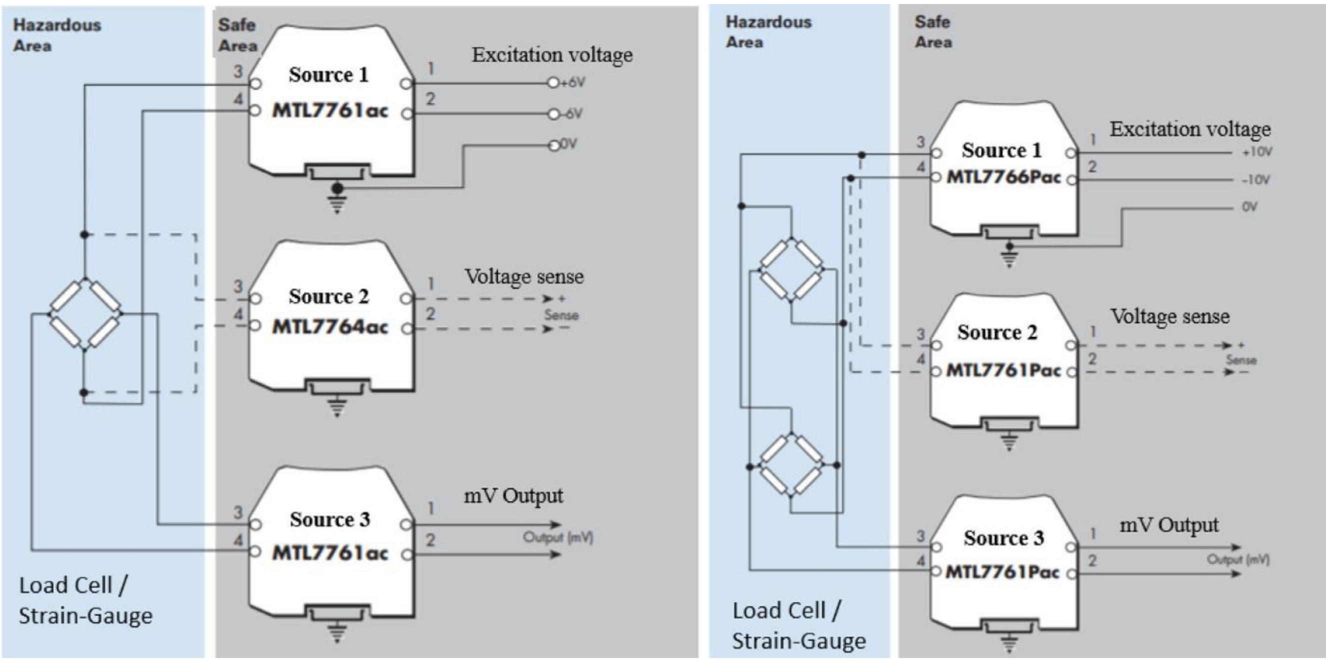


FIGURE 7 Load cell or strain gauge application that is connected to multiple sources[10]

no power is being applied, such as switches, plugs, sockets, and terminals, when used within its rated specification at an ambient temperature not greater than 40°C. The rated specification can be obtained from the manufacturer's datasheet. However, in practice, the IS system is rarely designed for T6 (85°C) temperature classification, as the only gas listed in the available documentation requiring a T6 temperature classification is carbon disulfide (CS_2). The application of carbon disulfide gas in the industry is rare because of its toxicity. Therefore, a T4 (135°C) classification is adequate. A claim of T6 is predominantly a marketing tool rather than a requirement. Table 3 provide T4 classification for simple apparatus according to IEC/EN 60079-14, section 16.4.

According to the IEC 60079-14, the temperature classification of a simple apparatus with a surface area of 20mm^2 or more will be T4 if the input power is less than 1.3 W with the maximum ambient temperature at 40°C. The corresponding powers for higher ambient temperatures are 1.2 W at 60°C and 1W at 80°C. For any condition outside the above range, this rule is not applicable. In that case, the maximum possible surface temperature has to be measured or assessed. For a thermocouple and an RTD, the temperature classification is determined by the maximum measured temperature.

Figure 5 shows an application of temperature measurement ranging from —50°C to 400°C. The measurement is done with an Ex field temperature transmitter head consisting of an earthed RTD as a basic sensing element mounted in Zone 0 with Ex ia IIC classification. The transmitter head is located in Zone 1 and converts the resistance to 4-20 mA current.

According to the IEC 60079-11, the IS system designer must demonstrate that the sensing element RTD complies with Simple Apparatus. RTD does not generate or store electrical energy of more than 1.5 V, 100 mA, and 25 mW. The safety in using RTD is not achieved by the inclusive of voltage or current-limiting devices. It does not have any means of increasing the available voltage or current. Therefore, it is a simple apparatus; no further certification is required. Take note that the circuit shall also be capable of withstanding an insulation test at 500 Vrms, according to IEC 60079-11 clause 6.3.12, and its terminals shall conform to 6.2.1. This has been described in Section 2.1.

3.2 | Safety evaluation process for simple IS system, the basic method

A simple IS system is a circuit that contains one associated apparatus (one source), one field device with zero internal field device capacitance (Ci) and/or zero internal field device inductance (Li). A nonsimple IS system is a mixed circuit consisting of single or several sources, single or multiple field devices, SPDs, or any connected device with a nonzero value for both Ci and Li.

The majority of intrinsically safe systems are simple IS systems that contain a single source of power from a single safety barrier connected to a single piece of intrinsically safe apparatus with either Ci or Li at zero, out in the field. For simple IS circuitry with only one source supplying current, voltage, and power to the field, IS verification can easily be made by comparing the safety parameters, as shown in Figure 6. Any system that can fulfill Equations (1)-(5) (safety evalutions equations are shown in Figure 6) will be intrinsically safe. In practice, the user needs to consider both safety and operational requirements. For example, besides the safety consideration, it must have sufficient voltage to drive the field device. Only

TABLE 4 The 1% and 50% ruling on maximum external connectable capacitance and inductance (Co and Lo value)

Field Device Impedance = Lumped Impedance (Ci and Li)	Cable Impedance = Distributed Impedance (Cc and Lc)	Verification method
Ci = 0; Li = 0	Cc ≠ 0 or Cc = 0; Lc ≠ 0 or Lc = 0; Regardless of the value	Basic verification method using Equations (1)–(5) Original Co and Lo are used
Ci ≠ 0; Li = 0	Cc ≠ 0 or Cc = 0; Lc ≠ 0 or Lc = 0; Regardless of the value	Basic verification method using Equations (1)–(5) Original Co and Lo are used
Ci = 0; Li ≠ 0	Cc ≠ 0 or Cc = 0; Lc ≠ 0 or Lc = 0; Regardless of the value	Basic verification method using Equations (1)–(5) Original Co and Lo are used
Ci ≠ 0; Li ≠ 0	Cc ≠ 0 or Cc = 0; Lc ≠ 0 or Lc = 0 Regardless of the value	1. Further evaluation is needed. 2. Check that Ci ≤1% × Co or (either but not both) Li ≤1% × Lo then use Equations (1)–(5) basic verification method with original Co and Lo 3. If Ci >1% × Co and Li >1% × Lo then the new Co (new) and new Lo (new) will be applied. Co (new) = 50% × Co (original); Lo (new) = 50% Lo (original) 4. Only calculation with new Co and new Lo that satisfied Equations (1)–(5) is intrinsically safe

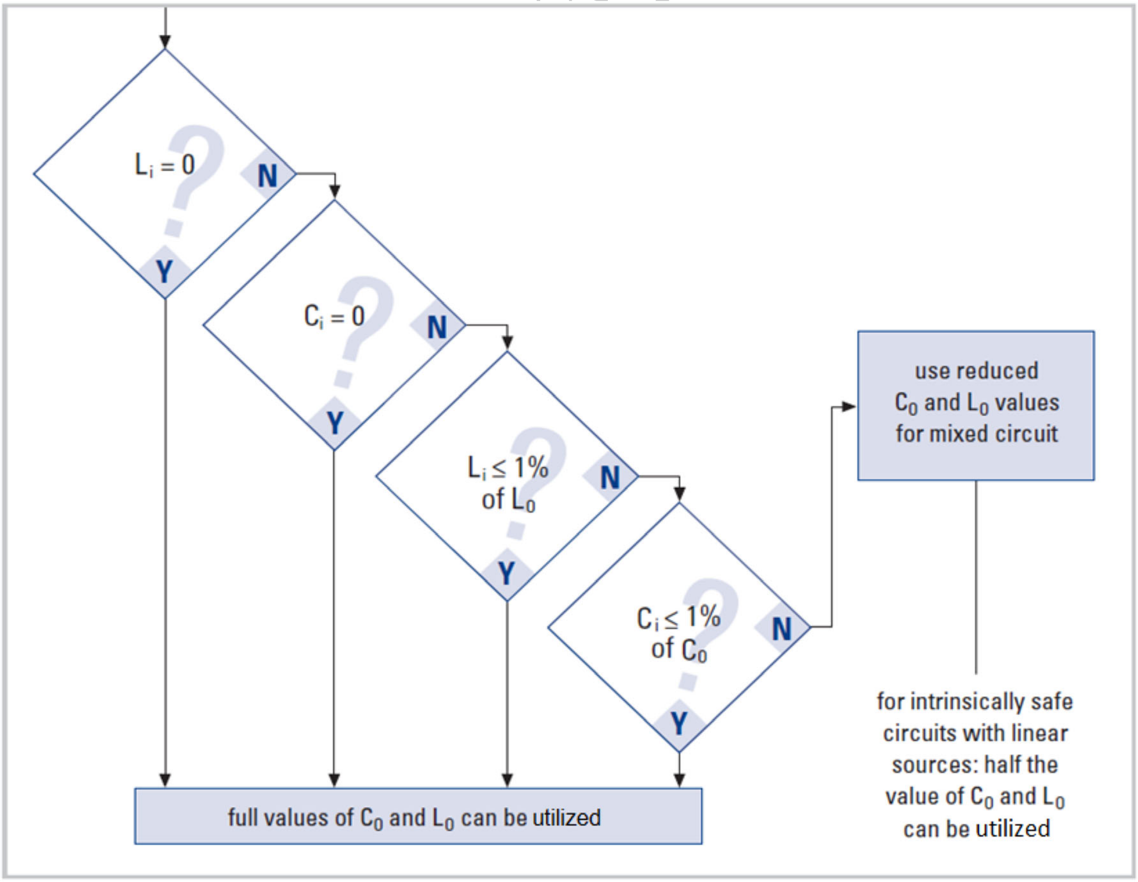


FIGURE 8 Assessment ruling on Co and Lo values for mixed circuits with linear sources[11]

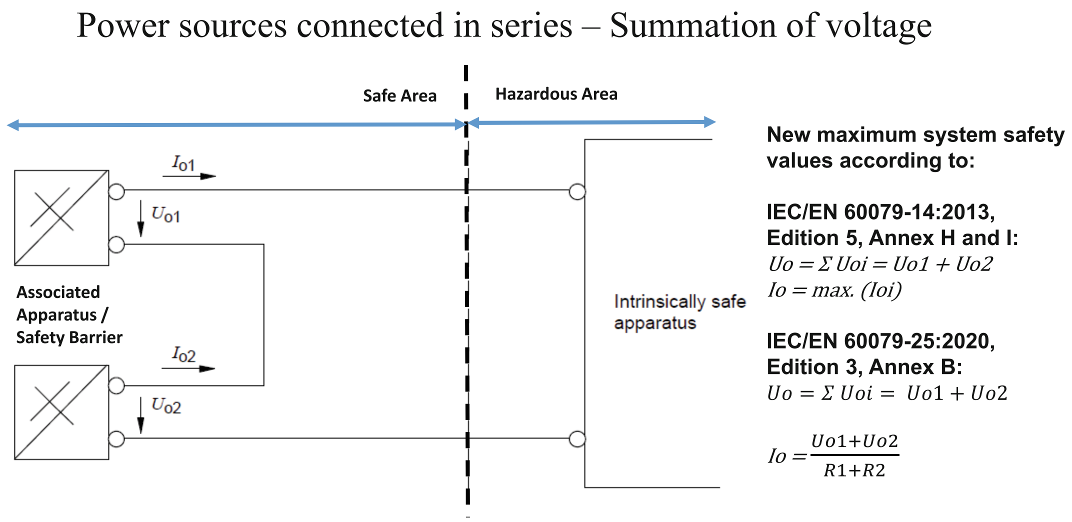


FIGURE 9 Intrinsically safe circuit, physically connected in series to several linear output associated apparatus

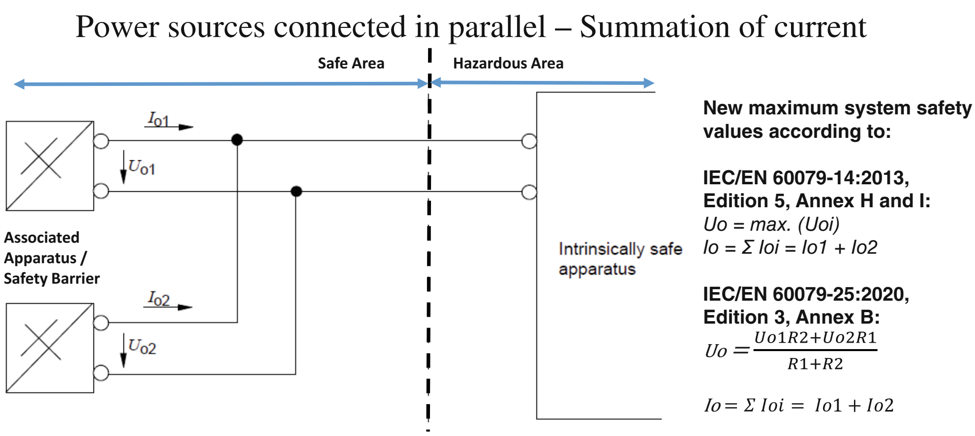


FIGURE 10 Intrinsically safe circuit, physically connected in parallel to several linear output associated apparatus

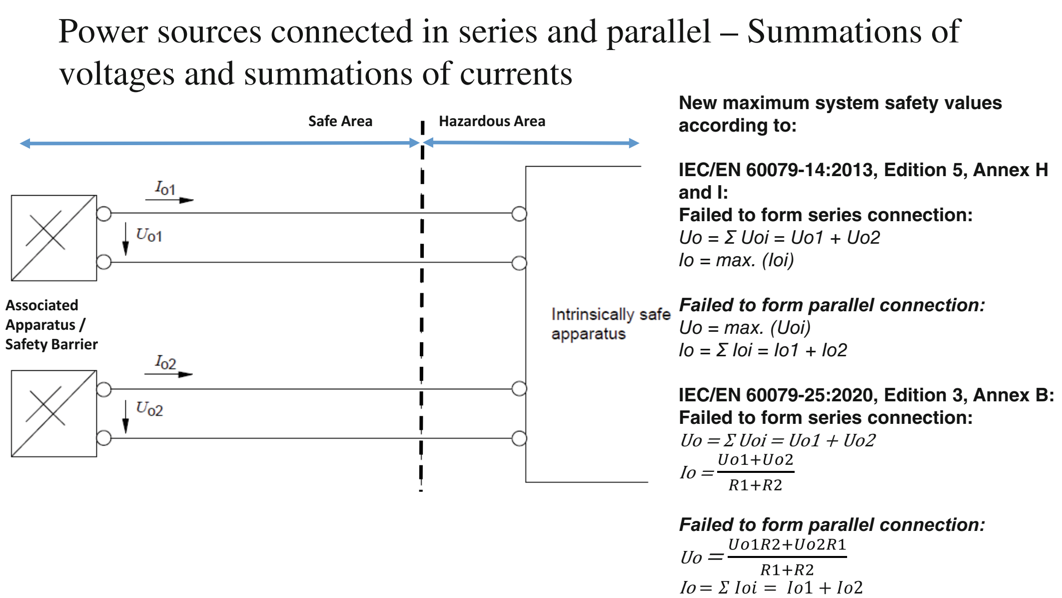


FIGURE 11 Intrinsically safe circuit series and parallel connection with several linear output associated apparatus

TABLE 5 Permitted capacitance Co extracted from IEC/EN 60079-11: 2011 Annex A

Permitted capacitance μF		
	Group IIC apparatus With safety factor of	
Voltage Uo	×1	×1.5
29.6	0.229	0.070
29.7	0.226	0.069
29.8	0.224	0.068
29.9	0.222	0.067
30.0	0.220	0.066
30.2	0.215	0.065
30.4	0.210	0.064
30.6	0.206	0.0626
30.8	0.202	0.0616

systems that fulfill both safety and operational requirements will be implemented.

3.3 | IS verification for a non-simple IS system with a linear source

Most of the available literature on the study of IS and the given examples only evaluate the safety according to Equations (1)–(5) with a single source and a single field device. A single source means a single IS isolator or a single safety barrier. However, many systems come with more than one field device and multiple sources in the actual application. For example, a field transmitter is connected to two SPDs with a loop-powered indicator before connecting to a safety barrier. Another example is the load cell application, which requires three sources (three safety barriers), as shown in Figure 7. Excitation voltage to power the load cell, voltage sense, and load cell mV output requires one safety barrier each. In many cases, there are also different combinations of Ex i field devices and safety barriers from different manufacturers.

For safe usage, the user or system operator must demonstrate and document the “proof of intrinsic safety” to ensure that the respective connection does not produce incentive sparks and hot surfaces. This process offers the user the advantage of selecting and combining Ex i field devices and safety barriers from different manufacturers according to the specific requirements. A document confirming the safety of the whole system is then produced using the information from the individual apparatus certificates, according to the system standard IEC 60079 parts 11, 14, and 25 or ANSI/ISA-RP 12.06.01, as well as the local requirements. This system documentation also includes details of cable types and simple apparatus used in the system.

A non-simple IS system could consist of interconnected cables with several sources and/or several field devices, which contribute to the distributed and lumped impedance. Distributed impedance is the

TABLE 6 Intrinsically safe calculation for simple IS system

Sequence step	Device / Model / Parameter	Temperature transmitter STT850 SmartLine	Type A instrument cable (300 M) A7BT2-P050L	Safety barrier/interface MTL 5541	Application requirement	Compliances	Remark
1	Level of protection	ia		ia	ia	Yes	
2	Gas group	IIC		IIC	IIC	Yes	
3	Temperature classification	T4		N.A.	T4	Yes	
4	Ambient temperature	−40°C to +70°C	−40°C to +65°C	−20°C to +60°C	−20°C to +60°C	Yes	
5	Parameter comparison						
	Voltage	Ui: 30 V		Uo: 28 V		Yes	Ui ≥ Uo; Equation (1)
	Current	Ii: 225 mA		Io: 93 mA		Yes	Ii ≥ Io; Equation (2)
	Power	Pi: 900 mW		Po: 650 mW		Yes	Pi ≥ Po; Equation (3)
6	Cable parameters						
	Capacitance	Ci: 4 nF	Cc = 300 × 120 pF = 36 nF	Co: 83 nF		Yes	Ci + Cc ≤ Co; Equation (4)
	Inductance	Li: 0 μH	Lc = 3.69 × 40 μH = 147.6 μH	Lo: 4.2 mH		Yes	Li + Lc ≤ Lo; Equation (5)
7	Isolation	Isolated	Not Applicable (N.A.)	Isolated	Isolated	Yes	

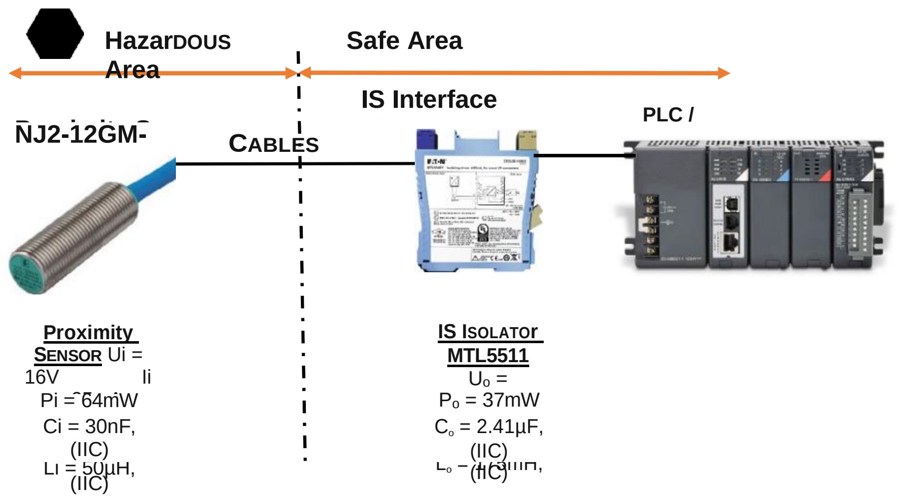


FIGURE 12 Valve opening and closing detection with a proximity sensor

impedance distributed over the length of the cable (Cc and Lc value). Lumped impedance is the sum of the impedance from all the concentrated field apparatus (Ci and Li value).

According to IEC/EN 60079-11: 2011 Edition 6, an IS system, regardless of the value of distributed impedance, with either zero lumped capacitance Ci or zero lumped inductance Li, will be evaluated using the basic verification method, Equations (1)–(5) with the original maximum external connectable capacitance and inductance (Co and Lo value). The original Co and Lo are obtained from the IS certificate. Regardless of the value of distributed impedance, if the lumped capacitance Ci and inductance Li are greater than zero, further investigation will be required. If the sum of all Li or Ci in each circuit is more than 1% of Lo and Co, it is a mixed circuit with an increased ignition hazard. If this is the case, the output values Lo and Co must be reduced by 50%. This is known as a "50% ruling," which is illustrated in Table 4. The 50% reduction in Co (new Co) and Lo (new Lo) is used for evaluation in Equations (1)–(5). When the new Co is greater than 1 μF, it will be taken as 1 μF for Groups I, IIA, and IIB and 600 nF for Group IIC per IEC/EN 60079-11: 2011 Edition 6, Clause 10.1.5.2.

Figure 8 provides a flow chart on the safety assessment rules for reducing Co and Lo values in mixed circuits with linear sources in compliance with IEC/EN 60079-11: 2011 Edition 6.

3.3.1 | Verification of intrinsically safe circuit with more than one linear power source (safety barrier)

A non-simple IS mixed circuit could consist of several power sources. Under fault conditions, the supply sources could be shorted as parallel or series connections. Therefore, the value for voltage (Uo), current (Io), and power (Po) could rise higher than in the case of a single source simple IS system. In other words, for safety verification, a new set of system safety parameters (Uo, Io, Po, Co, and Lo) needs to be established.

For linear output characteristic power sources, the IEC recommended two methods to establish the new set of system safety parameters to verify the compliance with intrinsically safe methodology. Both methods provide slightly different values, but both values are accepted. The user is advised to be consistent. Use only one of them throughout the complete evaluation. They are:

IEC/EN 60079-14:2013, Edition 5, Appendix H and I.

IEC/EN 60079-25:2020, Edition 3, Appendix B.

Figure 9 shows the linear output power sources physically connected in series and how they establish the new system safety parameters for verification according to IEC/EN 60079 parts 14 and 25.

3.3.2 | Example to establish the new system safety parameters

Uo1 = 10 V	Uo2 = 20 V
Io1 = 10 mA	Io2 = 20 mA
Po1 = 25 mW	Po2 = 100 mW
R1 = 10 V/10 mA = 1 kΩ	R2 = 20 V/20 mA = 1 kΩ

3.3.3 | Verification according to IEC/EN 60079-14:2013, Edition 5, Appendix H and I

New system safety parameter

$Uo = \sum Uoi = Uo1 + Uo2 = 10\ V + 20\ V = 30\ V.$

$Io = \max.(Ioi) = 20\ mA.$

$Po = 0.25 \times Uo \times Io = 0.25 \times 30\ V \times 20\ mA = 150\ mW.$

3.3.4 | Verification according to IEC/EN 60079-25:2020, Edition 3, Appendix B

New system safety parameter

$Uo = (Uoi = Uo1 + Uo2 = 10\ V + 20\ V = 30\ V.$

$Io = (Uo1 + Uo2)/(R1 + R2) = 30\ V/2\ k\Omega = 15\ mA.$

$Po = Po = 0.25 \times Uo \times Io = 0.25 \times 30\ V \times 15\ mA = 112.5\ mW.$

Figure 10 shows the linear output power sources physically connected in parallel and how they establish the new set of system safety parameters for verification according to the IEC/EN 60079 parts 14 and 25.

TABLE 7 Intrinsically safe verification for a nonsimple IS lumped circuit

Sequence step	Device / Parameter	Proximity sensor	Cable	Safety barrier/interface	Application requirement	Compliances	1% ruling	50% Ruling applied when both lumped Ci ≥1% × Co and lumped Li ≥1% × Lo 50%	Final compliances	Remark
1	Level of protection	ia		ia	ia	Yes			Yes	
2	Gas group	IIC		IIC	IIC	Yes			Yes	
3	Temperature classification	T4		N.A.	T4	Yes			Yes	
4	Ambient temperature	100°C	−40°C to +65°C	−20°C to +60°C	60°C	Yes			Yes	
5	Parameter comparison									
	Voltage	Ui: 16 V		Uo: 10.5 V		Yes			Yes	Ui ≥ Uo; Equation (1)
	Current	Ii: 25 mA		Io: 14 mA		Yes			Yes	Ii ≥ Io; Equation (2)
	Power	Pi: 64 mW		Po: 37 mW		Yes			Yes	Pi ≥ Po; Equation (3)
6	Cable parameters									
	Capacitance	Ci: 30 nF	Cc = 300 × 120 pF = 36 nF	Co: 2.41 μF		Ci and Li ≠ 0; Need further Investigation	1% × Co = 24.1 nF Ci >1% × Co	Only the lumped capacitance Ci >1% of Co, not the lumped inductance Li therefore original Co and Lo will be used	Yes	Lumped Ci + Cc = 66 nF ≤ Co (Original); Equation (4)
	Inductance	Li: 50 μH	Lc = 3.69 × 40 μH = 147.6 μH	Lo: 175 mH			1% × Lo = 1.75 mH Li <1% × Lo		Yes	Lumped Li + Lc = 197.6 μH ≤ Lo (Original); Equation (5)
7	Isolation	No		Isolated	Isolated	Yes			Yes	

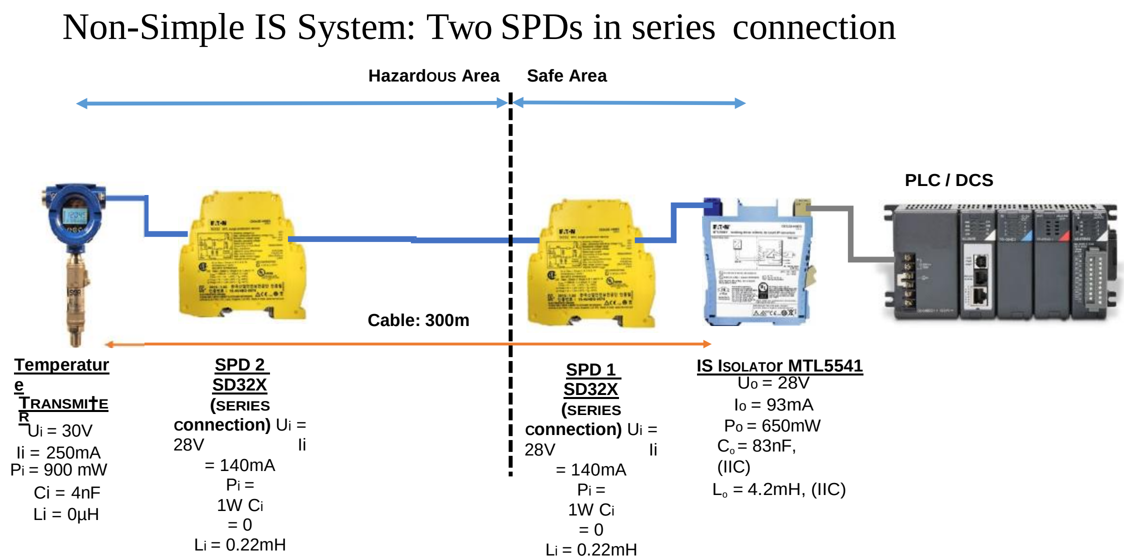


FIGURE 13 Entity parameter verification for two SPDs connected in series at the field[18]

3.3.5 | Based on the same example value, verification according to IEC/EN60079-14:2013, Edition 5, Appendix H and I

New system safety parameter

Uo = max. (Uoi) = 20 V.

Io = Σ Ioi = Io1 + Io2 = 10 mA + 20 mA = 30 mA.

Po = 0.25 × Uo × Io = 0.25 × 20 V × 30 mA = 150 mW.

3.3.6 | Verification according to IEC/EN 60079-25:2020, Edition 3, Appendix B

New system safety parameter

Uo = (Uo1R2 + Uo2R1)/(R1+R2) = (10 V × 1 kΩ + 20 V × 1 kΩ)/(1 kΩ + 1 kΩ) = 15 V.

Io = Σ Ioi = Io1 + Io2 = 10 mA + 20 mA = 30 mA.

Po = 0.25 × Uo × Io = 0.25 × 15 V × 30 mA = 112.5 mW.

Figures 9 and 10 show that the interconnection of the linear power sources is made under controlled conditions (deliberately connected). Then, the interconnections are considered to fail to open and short circuit, but the connections are not considered to reverse or change from a series into a parallel connection or a parallel connection into a series. However, in Figure 11, the power sources are not deliberately connected in series or parallel (not well defined); therefore, there is a possibility that when the circuit fails, the power sources become connected in series or parallel under certain circumstances. In this situation, evaluation for both series and parallel power source connections is required.

After determining the value for Uo, Io and Po, next will be the maximum value for equivalent external capacitance (Co) and inductance (Lo) allowed to connect externally to the Supply Sources. The Co and Lo value can be obtained from the ignition curves using Uo and Io with an appropriate safety factor (safety factor for Ex ia and Ex ib is 1.5; for Ex ic is 1.0): capacitance ignition curve (Figure 2A) for Co value and the inductance ignition curve (Figure 3A) for Lo value. For the Uo value of 30 V, the Co value taken from the curve will be based on 45 V (30 V × safety factor 1.5 = 45 V) and the value will be 60 nF for gas group IIC. For the Io value of 20 mA, the Lo value taken from the curve will be based on 30 mA (20 mA × safety factor 1.5 = 30 mA), and the value will be 90 mH for the gas group IIC. The value taken from the curve is always an approximate value. Alternatively, the Co value can be taken from the table provided by IEC/EN 60079-11: 2011 Annex A for a more accurate value where the tabulation is experimentally obtained. Table 5 provides extracted data from the tabulation.

The value of Co taken from the table is 66 nF (when taken from the curve, it is around 60 nF). When reading the value from the table, please take note that the table already has the safety factor value. Hence, the Uo is taken from the original value without any safety factor value (30 V, not 45 V, as shown above). In other words, the value taken from the curve needs to be multiplied by a safety factor value, but when taking it from the table there is no need, as the table already has the safety factor value.

For the value of Lo, there will be no tabulation table available. However, the value could be obtained by using energy stored in the inductor concept. Energy stored in the inductor is given by:

$$E = \frac{1}{2} L I^2, \quad (6)$$

where E is the energy in Joules, L is inductance in Henry, and I is the current in Ampere.

The minimum ignition energy in joules is given below. The data is also published on IEC/EN 60079-11:2011.

- Gas Group I apparatus: 525 µJ
- Gas Group IIA apparatus: 320 µJ
- Gas Group IIB apparatus: 160 µJ
- Gas Group IIC apparatus: 40 µJ

For Io = 20 mA (with a safety factor of 1.5 = 30 mA), gas group IIC (40 µJ), and the value of Lo = 88.89 mH. Take note that the safety factor is applicable (safety factor for Ex ia and Ex ib is 1.5; safety factor for Ex ic is 1.0) when using Equation 6.

TABLE 8 Intrinsically safe verification for nonsimple IS system with two SPDs in series connection

	Device	Temperature transmitter	Surge protection	Cable (300 M)	Safety barrier/ interface						
Sequence step	**Parameter**					**Application requirement**	**Compliances**	**1% ruling**	**50% ruling applied when both lumped Ci ≥1% × Co and lumped Li ≥1% × Lo 50%**	**Final compliances**	**Remark**
1	Level of protection	ia	ia		ia	ia	Yes			Yes	
2	Gas group	IIC	IIC		IIC	IIC	Yes			Yes	
3	Temperature classification	T4	T4		N.A.	T4	Yes			Yes	
4	Ambient temperature	−40°C to +70°C	−30°C to +75°C	−40°C to +65°C	−20°C to +60°C	−20°C to +60°C	Yes			Yes	
5	Parameter comparison										
	Voltage	Ui: 30 V	Ui: 28 V		Uo: 28 V		Yes			Yes	Ui ≥ Uo; Equation (1)
	Current	Ii: 225 mA	Ii: 140 mA		Io: 93 mA		Yes			Yes	Ii ≥ Io; Equation (2)
	Power	Pi: 900 mW	Pi: 1 W		Po: 650 mW		Yes			Yes	Pi ≥ Po; Equation (3)
6	Cable parameters										
	Capacitance	Ci: 4 nF	Ci: 0	Cc = 300 × 120 pF = 36 nF	Co: 83 nF		Lumped Ci and Li ≠ 0; Need further investigation	1% × Co = 0.83 nF Lumped Ci <1% × Co	Only the lumped Li >1% of Lo, not the lumped Ci therefore original Co and Lo will be used	Yes	Lumped Ci + Cc = 40 nF ≤ Co (Original); Equation (4)
	Inductance	Li: 0 μH	Li: 0.22 mH × 2 = 0.44 mH	Lc = 3.69 × 40 μH = 147.6 μH	Lo: 4.2 mH			1% × Lo = 0.042 mH Lumped Li >1% × Lo		Yes	Lumped Li + Lc = 0.5876 mH ≤ Lo (Original); Equation (5)
7	Isolation	Isolated	N.A.	N.A.	Isolated	Isolated	Yes			Yes	

4 | RESULTS AND DISCUSSION

The following devices will be used for performing all the IS verification presented for Cases 1 to 4.

Field device: Temperature transmitter (Tx)	Associate electrical apparatus: Safety Barrier
Manufacturer: Honeywell	Manufacturer: Eaton
Model: STT850 SmartLine[12]	Model: MTL5541[10]
IS Certificate: Sira 14ATEX2046X	IS Certificate: Baseefa 07ATEX0213 Issue 7
Used for: Case 1, 3, and 4	Used for: Case 1, 3, and 4
Field device: Inductive proximity sensor	Associate electrical apparatus: Safety barrier
Manufacturer: Pepperl+Fuchs	Manufacturer: Eaton
Model: NJ2-12GM-N[11]	Model: MTL 5511[10]
IS Certificate: PTB 00 ATEX 2048 X	IS Certificate: Baseefa 07ATEX0211 Issue 7
Used for: Case 2	Used for: Case 2
Field device: Surge protection device (SPD 1)	Field device: Surge protection device (SPD 2)
Manufacturer: Eaton	Manufacturer: Eaton
Model: TP48-I-NDI[14]	Model: SD32X[15]
IS Certificate: Baseefa 04ATEX0251X Issue 6	IS Certificate: Baseefa 02ATEX0211X Issue 8
Used for: Case 4	Used for: Case 3 and 4
Field device: Loop powered process indicator (LI)	Interconnection cable: Type A Instrument Cable (300 M)
Manufacturer: Yokogawa	Manufacturer: Anixter
Model: MLX-A22-14-KU21[16]	Model: A7BT2-P050L[17]
IS Certificate: ITS13ATEX27856X	Specification: Conductor Size = 1.5 mm^2; Conductor Stranding =
Used for: Case 4	7/0.53; 120 pF/m; 12.3 Ω/km; 40 μH/Ω
	Used for: All cases.

Case 1. Intrinsically safe verification for simple IS system ($Ci \neq 0$; $Li = 0$): Single field device and a single IS isolator.

4.1 | Application: Temperature measurement

The simplified connection diagram is shown in Figure 6, where the field device is the temperature transmitter, and the IS interface is MTL 5541 with a 300 m interconnection cable.

Table 6 provides a summary of the IS verification safety calculation for a simple IS system in sequence steps. All specifications and parameters are taken from the actual manufacturer's datasheet and certificate. The analysis proves that it complied with Equations (1)-(5). Therefore, the system is intrinsically safe.

Case 2. Intrinsically safe verification for Nonsimple IS System with a lumped circuit (Lumped $Ci \neq 0$ and Lumped $Li \neq 0$).

4.2 | Application

Valve opening and closing detection using an IS proximity sensor with the connection, as shown in Figure 12.

Table 7 provides a summary of the IS verification for a lumped circuit. Only the lumped capacitance Ci is more than 1% of Co, not the lumped inductance Li; therefore, the original Co and Lo will be used. From the analysis, it is proven that the system is intrinsically safe.

For illustration purposes, assuming that both the lumped capacitance Ci and the lumped inductance Li exceed 1% of Co and 1% of Lo, respectively, then the 50% reduction on Co and Lo will be applicable. Note that after the 50% reduction, if the new Co value exceeds 600 nF, 600 nF will be used. To comply with the IEC/EN 60079-11 Clause 10.1.5.2, for Gas Group IIC, the maximum Co is 600 nF.

Co (New) = 50% × 2.41 μF = 1.205 μF.

Exceeding 600 nF, therefore Co (New) = 600 nF.

Case 3. Intrinsically safe verification for nonsimple IS system with a temperature transmitter where two SPDs protect the loop in series connection (Lumped $Ci \neq 0$; Lumped $Li \neq 0$).

4.3 | Application

Temperature measurement is performed using a temperature transmitter with two SPDs connected in series, as shown in Figure 13.

Table 8 provides the sequence steps for evaluation. Only the lumped Li value exceeds 1% of Lo, not the lumped Ci; therefore, the original Co and Lo will be used for the verification. From the analysis, it is proven that the system is intrinsically safe.

Case 4. Intrinsically safe verification for a nonsimple IS system with a temperature transmitter, two SPDs with series and parallel connection and a loop-powered indicator (Lumped $Ci \neq 0$; Lumped $Li \neq 0$).

4.4 | Application

Temperature measurement is made using a temperature transmitter with one loop-powered indicator (to display the temperature reading remotely). The circuit loop is also protected by two SPDs. One of the SPDs is connected in parallel, and another one is connected in series,

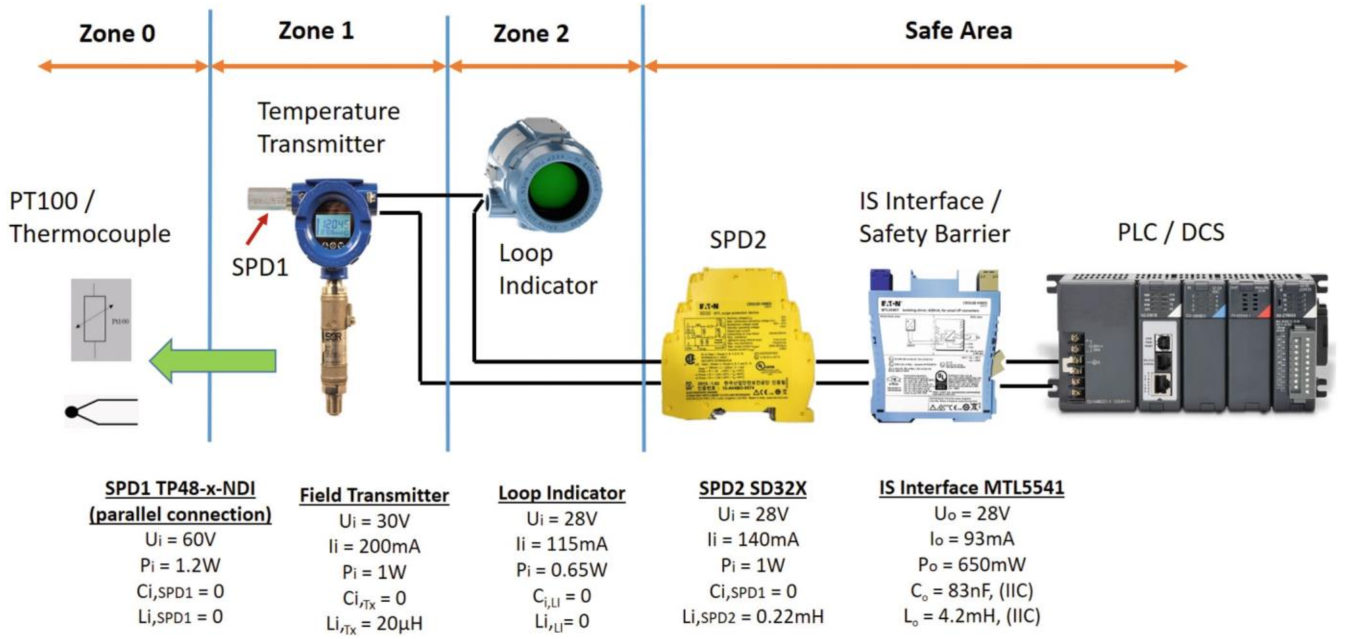


FIGURE 14 Non-simple intrinsically safe circuit mounted in different zoning areas with mixed lumped impedance

as shown in Figure 14. The different field devices are mounted at different zoning areas.

The sensing element is either RTD or thermocouple, so it should be assessed as a simple apparatus, as described in Section 3.1. above. However, for this kind of application, in practice, the sensing element is supplied together with the temperature transmitter in which the issued IS certificate already covers the assessment. In other words, it is already pre-assessed by the transmitter manufacturer. Therefore, it is not necessary to carry out the assessment; the verification is then performed on the whole transmitter, which already includes the sensing element.

Table 9 provides the sequence steps for intrinsically safe evaluation. The lumped value of the Ci and Li does not exceed 1% of Co and Lo; therefore, the original Co and Lo will be used for the verification. From the analysis, it is proven that the system is intrinsically safe.

Conditions that may cause the verification to fail:

Generally, before an IS field device is designed and produced, all the field device manufacturers will communicate with the IS interface manufacturer. This ensures that their product is supported by the off-the-shelf IS isolator unless the field device manufacturer wishes to produce their own IS isolator. Therefore, for a simple IS system (a single field device and a single power source), it is easy to verify that the system is intrinsically safe, as shown in Case 1. In this case, the only parameter that could cause the verification to fail will be the cable length and its specification. (A) and (B) calculations will determine the maximum installation cable distance.

Cable parameter for Case 1 (From Table 6):

$Ci + Cc \le Co => Cc \le Co - Ci => Cc \le 4\ nF - 83\ nF = 79\ nF$

Therefore, cable distance $= \frac{Cc}{120\ pF} = \frac{79\ nF}{120\ pF} = 658$ m (A)

$Li + Lc \le Lo => Lc \le Lo - Li => Lc \le 4.2$ mH.

Therefore, the cable distance should not exceeds 658 m (B)

Hence, from (A) and (B), the maximum cable distance that could pass the verification will be 658 m. Any cable longer than 658 m will cause the verification to fail. If the field installation required a longer distance than 658 m, the way forward would be to use a better specification and a bigger cable size. Most of the time this situation is due to the cable capacitance.

The factor causing the simple IS system to fail the validation is easily identified and rectified. This will not be as easy for a non-simple IS system; for example, Cases 2 to 4. As an IS system is a system approach, any interconnected device, including the cable in the loop, could contribute to the safety verification. Therefore, device selection will be necessary; whenever possible, try to use a field device with a lower Ci and Li value. Some field device manufacturers use a diode embedded into their design to suppress the CI and Li value. This is commonly seen in the design of an IS solenoid, where Ci and Li are zero.

5 | SUMMARY

- Per IEC/EN 60079-14, before commissioning an intrinsically safe circuit, it is mandatory to carry out the "verification of intrinsic safety" with documented justification. Once the intrinsic safety has been verified, the installer's responsibility is to complete the installation according to the control drawing, installation code of practice and the local requirements.
- Regardless of the distributed impedance, an IS system where the lumped impedance is greater than 1% of Co and Lo will be

TABLE 9 Intrinsically safe verification calculation for nonsimple IS system with a temperature transmitter, loop-powered indicator and SPDs

	Device	Temperature transmitter	Parallel SPD	Loop indicator	Cable (300 M)	Series SPD	Safety barrier/ interface						
Sequence step	Parameter							Application requirement	Compliances	1% ruling	50% ruling applied when both Lumped Ci ≥1% × Co and lumped Li ≥1% × Lo 50%	Final compliances	Remark
1	Level of protection	ia	ia	ia		ia	ia	ia	Yes			Yes	
2	Gas group	IIC	IIC	IIC		IIC	IIC	IIC	Yes			Yes	
3	Temperature classification	T4	T6	T4		T4	N.A.	T4	Yes			Yes	
4	Ambient temperature	−40°C to +70°C	−40°C to +60°C	−40°C to +80°C	−40°C to +65°C	−30°C to +75°C	−20°C to +60°C	−20°C to +60°C	Yes			Yes	
5	Parameter comparison												
	Voltage	Ui: 30 V	Ui: 60 V	Ui: 28 V		Ui: 28 V	Uo: 28 V		Yes			Yes	Ui ≥ Uo; Equation (1)
	Current	Ii: 225 mA	Ii = Io	Ii: 115 mA		Ii: 140 mA	Io: 93 mA		Yes			Yes	Ii ≥ Io; Equation (2)
	Power	Pi: 900 mW	Pi: 1.2 W	Pi: 0.65 W		Pi: 1 W	Po: 650 mW		Yes			Yes	Pi ≥ Po; Equation (3)
6	Cable parameters												
	Capacitance	$Ci_{,Tx}$: 4 nF	$Ci_{,SPD1}$: 0	$Ci_{,LI}$: 0	Cc = 300 × 120 pF = 36 nF	$Ci_{,SPD2}$: 0	Co: 83 nF		Lumped Ci and Li ≠ 0; Need further investigation	1% × Co = 0.83 nF Lumped Ci <1% × Co	Both lumped Ci and Li is less than 1% of Co and Lo therefore original Co and Lo will be used	Yes	Lumped Ci + Cc = 40 nF ≤ Co (Original); Equation (4)
	Inductance	$Li_{,Tx}$: 0 μH	$Li_{,SPD1}$: 0	$Li_{,LI}$: 0	Lc = 3.69 × 40 μH = 147.6 μH	$Li_{,SPD2}$: 0.22 mH	Lo: 4.2 mH			1% × Lo = 0.042 mH Lumped Li <1% × Lo		Yes	Lumped Li + Lc = 0.3676 mH ≤ Lo (Original); Equation (5)
7	Isolation	Isolated	N.A.	N.A.	N.A.	N.A.	Isolated	Isolated	Yes			Yes	

evaluated with a 50% reduction in Co and Lo value. Otherwise, the original Co and Lo value will be applied.

- When verifying a non-simple IS system where 50% ruling on Co and Lo is applied, if the new Co is greater than 1 μF, it will be taken as 1 μF for gas groups I, IIA, and IIB and 600 nF for gas group IIC per IEC/EN 60079-11: 2011 Edition 6, Clause 10.1.5.2.
- A non-simple IS mixed circuit could consist of several power sources. Under fault conditions, the supply sources could be shorted to become parallel or series connections. For verification, the resultant Uo and Io need to be determined. Using the resultant Uo and Lo, the new Co and Io can be determined from capacitive and inductive ignition curves with an appropriate safety factor. Alternatively, the Co value can be taken from the table tabulation found in IEC/EN 60079-11: 2011 Annex A for better accuracy. The Lo value can be obtained using the energy stored in the inductor equation, $E = \frac{1}{2} LI^2$. The value of E is taken from the minimum ignition energy in joules for Group I apparatus is 525 μJ; Group IIA apparatus is 320 μJ; Group IIB apparatus is 160 μJ; for Group IIC apparatus is 40 μJ.
- SPD could be connected in series and parallel depending on the application; it is not a simple apparatus. Therefore, it needs to be certified for use in a hazardous area.

AUTHOR CONTRIBUTIONS

Kuew Wai Chew: Formal analysis (supporting); investigation (supporting); project administration (lead); supervision (lead); validation (supporting); writing – review and editing (supporting). Kein Huat Chua: Formal analysis (supporting); investigation (supporting); project administration (supporting); supervision (supporting); validation (supporting); writing – review and editing (supporting). Teik Hua Kuan: Conceptualization (lead); data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); project administration (equal); resources (equal); validation (lead); writing – original draft (lead); writing – review and editing (lead).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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