Innovative intrinsically safe concepts open up new perspectives in explosion protection - but they also require new test methods

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The ignition behaviour of an electric circuit can be strongly influenced by innovative hardware which triggers, in the case of a failure (e.g. the occurrence of sparks), a clearly defined behaviour of the circuits. For this purpose, however, novel, safety-relevant requirements are necessary which have so far not been included in the international standard IEC 60079-11: 2006 for the type of protection intrinsic safety - "i".

In this paper, we will present the "Power-i" technology. This technology meets the essential safety-relevant requirements and is based on the dynamic recognition and mastering of safety-critical conditions. As this technology also brings about an increase in the active power, new fields of application open up for the type of protection intrinsic safety - "i".

As the testing and certification of this technology is currently difficult at the international level, the aim is to anchor the safety-relevant specifications in the international standardisation (e.g. IEC 60079-11 or 60079-25 or a Technical Specification). In cooperation with internationally operating manufacturers and test centres, an international standard is aimed at which will enable global interoperability and will make it as easy as possible to provide proof of intrinsic safety.

1 Motivation

At present, no test instruction exists which is known internationally for the safety evaluation of "Power-i"-systems. Thus, a global marketing of this technology - which promises to bring about many economic advantages - is possible only to a limited extent, although the basic concept of the world-wide recognized type of protection intrinsic safety - "i" is definitely complied with. In this paper, we will prove that the safety-relevant requirements are fulfilled, and a suitable test procedure will be presented.

2 Power-i-systems

2.1 Definition

A "Power-i"-system encompasses electric circuits which, in normal operation, i.e. in the working range, operate with voltage values and/or current values which can lie outside the values defined in Annex A of the IEC 60079-11:2006. If, however, the test conditions are applied which are defined in Annex B of this IEC, no reliable statement can be made with regard to the duration of the active operating condition during the testing time. And hence, no reliable statement can be made with regard to ignition capability of the circuits or systems to be tested.

"Power-i" is based on a targeted influence of the source on any kind of spark formation, whereby a return to normal operation must not be possible before the critical state (sparks) has ended.

In the case of such circuits, the system "source, circuit and load" has to be assessed as an entity under safety-relevant aspects.

2.2 Advantages

The main advantage of the "Power-i"-technology is that - if all the positive characteristics of intrinsic safety are maintained - distinctly more intrinsically realisable active power is available in the explosion-hazardous area.

This means that, for example, maintenance and reconstruction work can be carried out with clearly increased power during the normal operation, without the need of having a permission to work on energised systems. With "Power-i", also time-consuming - and thus expensive - types of protection, such as "increased safety" - "e" or flameproof enclosure - "d", can be replaced in many applications by "intrinsic safety" - "i". This opens up new fields of application for the type of protection "intrinsic safety", especially in the process industry, for example in the following areas: weighing instruments, illuminating systems, valve controls and field buses like FOUNDATION Field bus H1 or PROFIBUS PA. This technology can easily be integrated in already existing and new technologies and makes existing applications simpler for plant manufacturers and operators.

A concrete technology that has been derived from "Power-i" is the DART® technology (DART: Dynamic Arc Recognition and Termination) which has been developed in many years of intensive research and investigations. Thanks to "Power-i", distinctly higher intrinsically realisable active powers are available (see Table 1) - compared to present-day solutions.

	U_{out}	P_{out}	Cable length
Power-i	50 VDC	approx. 50 W	100 m
	24 VDC	approx. 22 W	100 m
	50 VDC	approx. 8 W	1000 m
Power supply Ex i	16 VDC	approx. 320 mW	1000 m
Power-i/DART field bus	24 VDC	approx. 8 W	1000 m
FISCO field bus	12.8 VDC	approx. 1.4 W	1000 m

Table 1: Active power values attainable with "Power-i"

2.3 In how far is this new technology compatible with the conventional approach of intrinsic safety according to IEC 60079-11: 2006?

We will explain this by means of an example taken from Annex A of IEC 60079-11 Figure A.1 (see Figure 1 below). If a supply voltage of U = 24 VDC is specified and the safety factor

SF = 1.5 is taken into account, I = 174 mA are permitted for the current here in explosion group II C (in the case of the safety factor SF = 1.0, I = 261 mA results) . From this, a realisable intrinsically safe active power of P = 1.04 W can be determined if there is power matching.

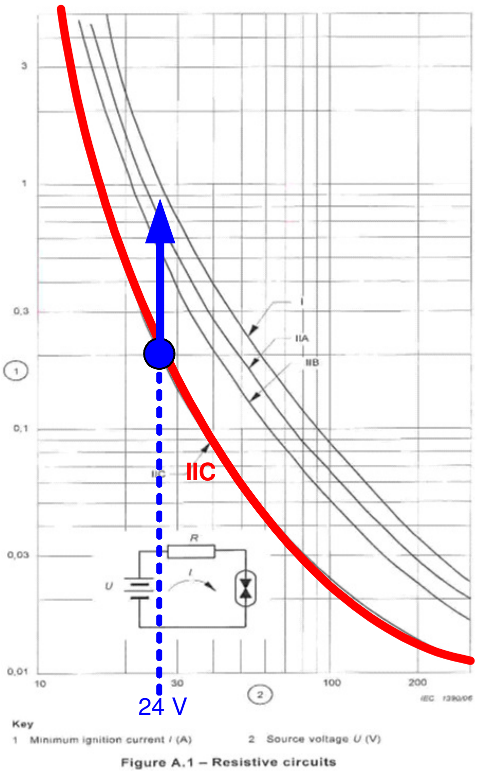

Figure 1. Working range of "Power-i" in the resistive characteristics field IEC 60079-11: 2006 (Figure A.1) for U = 24 VDC

By using the "Power-i" technology, a considerable increase in the intrinsically admissible current (I > > 174 mA) is possible (see arrow in Figure 1). The exact specification of this maximum permissible current value depends on the dynamic characteristics of the overall system "source + circuit + load". Thus, with "Power-i", under certain conditions 22 W are intrinsically realisable, as Table 1 shows, for example, for U = 24 VDC.

2.4 What is the reason for this behaviour?

In the case of the conventional approach (on the basis of IEC 60079-11: 2006), a spark can, in the resistive circuit, draw (ignition) energy from the source during the entire spark duration. A limit is set to this only by limiting the maximum current and the spark duration which is determined by the movement of the wire and the disc in the spark test apparatus.

In contrast to this, "Power-i" is based on a more complex approach.
Here, a rapid shutdown is used which recognizes a failure in the electrical system (e.g. a spark) already in the very moment of its occurence and immediately ensures a transition into a safe condition. By this, the conversion of ignitable spark energy is successfully prevented; this leads

to electrical connection values which are significantly higher than those which are currently admissible according to the IEC standard. Thereby, the fact is exploited that in resistive circuits, any safety-critical condition is directly associated with a - though only slight - current change. This change must be safely detected by current sensors and must effect the above-described transition into a safe condition, for example by shutdown. The detection of the current change must not be affected negatively by any other component of the overall system.

2.5 Which properties must a "Power-i" energy supply exhibit?

The afore-mentioned behaviour can be realised, e.g., with the hardware concept shown in Figure 2. The energy supply shown here comprises comparators for the detection of current steps (+di/dt detector for make sparks and –di/dt detector for break sparks) and overcurrents (I detector), conventional intrinsically safe limitation devices as well as an electronic switch S1. The internal resistance R_{Start} ensures - when the switch S1 is open - that only a "small" intrinsically safe current can flow into the load circuit complying with IEC 60079-11: 2006.

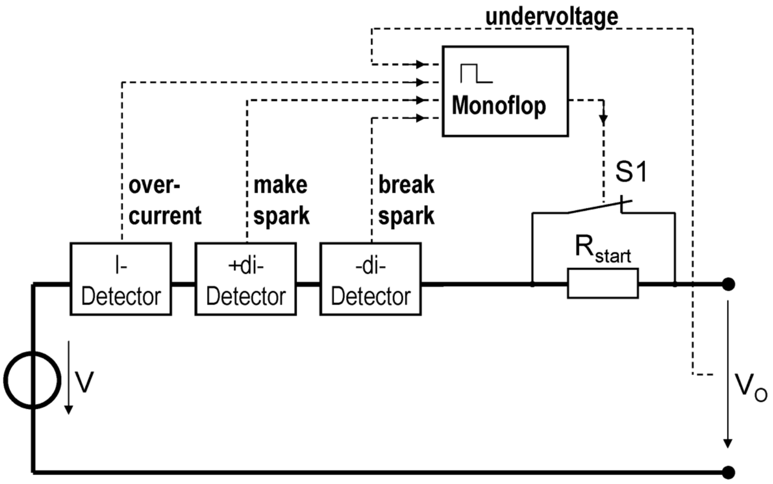

Figure 2. Basic circuit of a "power-i" energy supply

The behaviour shall be illustrated taking the U-I output set of characteristic curves of a "Power-i" source according to Figure 2 as an example (see Figure 3).

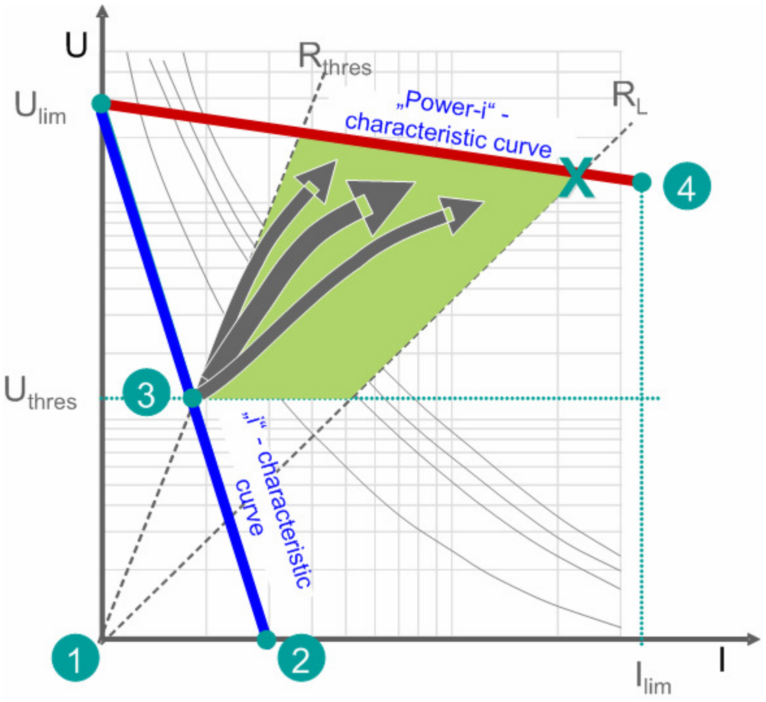

Figure 3. Output set of characteristic curves of a "Power-i" source during load connection

Basically, this set of characteristic curves consists of two different ranges of characteristic curves - the "i" characteristic curve, i.e. the starting and the return range, and the "Power-i" characteristic curve, i.e. the normal or working range.

1. "i" characteristic curve: (switch S1=open). This curve is completely situated in the intrinsically safe area of the family of characteristics according to IEC 60079-11:2007 Annex A. The run of this characteristic is determined by the linearly limiting source resistance R_{Start} (see Figure 2). The source resistance must attain a specified threshold value U_{thres} (Point 3 at R_{thres}) as a function of the load; otherwise, the transition into the range of the "Power-i" characteristic is not possible.
2. "Power-i" characteristic: (Switch S1=closed) Only after exceeding the threshold value U_{thres} does the "slow" transition from the range of the "i" characteristic into the "Power i" range take place. "Slow" transition means that the current change di/dt is below the minimum triggering value of the dynamic shutdowns. The "Power-i" range is the operating range which permit the maximum output power (in P4). This range is usually clearly above the "i" characteristic (and thus also outside the values specified in the IEC-60079-11:2007 Annex A).
3. If a current change di/dt is detected in this operating range due to failures on the side of the load (e.g. sparks) which is above the minimum triggering value for the dynamic shutdown (see Figure 4), this directly and very quickly leads to the return to the intrinsically safe range of the "i" characteristic due to the immediate opening of the electronic switch S1.

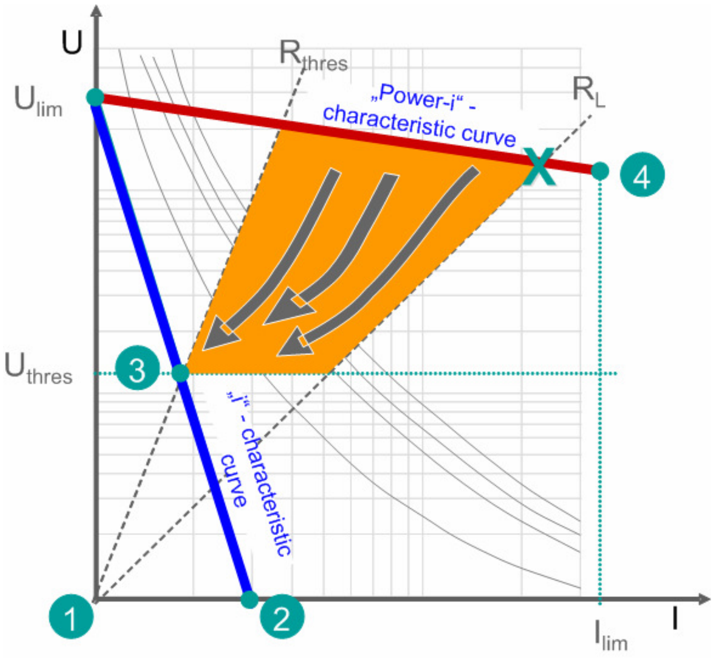

Figure 4. Output set of characteristic curves of a "Power-i" source in the case of a failure

Whereas the transition of the "i" characteristic to the "Power-i" characteristic (starting) <u>can</u> take place slowly, i.e. in the ms range, the opposite way (shutdown) <u>must</u> take place in the range of a few µs.

2.6 The safety concept of "Power-i"

The general precondition for an ignition is the necessity to exceed a defined ignition temperature in an initial volume of the gas/air mixture. For this, the reaching of a certain energy density in this initial volume is necessary. As the energy density derives from the power consumption within a certain period of time, it can be deduced that the factor "time" is of fundamental importance during an ignition. By influencing the factor "time" in a well-aimed manner, the ignition behaviour can be strongly influenced. The present standard IEC 60079-11:2006 does not account for this circumstance.

Fundamental investigations carried out by PTB have shown that by influencing this factor in a defined way, clearly higher "intrinsically safe" threshold values can be reached. For optimization, however, a safety-related assessment of the three essential components of the overall system – source + circuit + load - is required (see Figure 5).

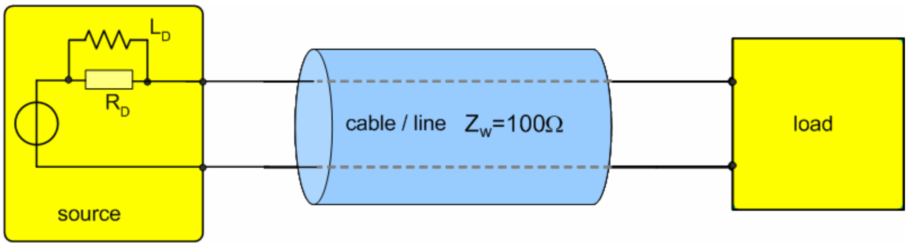

Figure 5. System components of a "Power-i" system

As a matter of principle, the information on a safety-relevant failure must, under no circumstances, be negatively influenced, neither by the circuit nor by the load, in such a way that a detection with a subsequent reaction of the source is no longer possible.

The most essential characteristics of the components of a "Power-i" system are:

⇒ **Source:**

The source must comprise the failure recognition and the shutdown according to the explanations provided in the previous sections.

⇒ **Circuit/cable**

The cable runtime and the signal interference by the circuit are safety-relevant and are significantly dependent on the cable parameters and the cable length.

⇒ **Loads:**

- should exhibit a defined starting behaviour (in the moment of starting, the resistance should, for a short time, lie far above the load resistance under normal operating conditions);
- should start slowly and without current steps;
- must ensure, by their electrical behaviour in the moment the circuit is opened, a defined di/dt step in the spark transition range;
- must not influence the safety-relevant information on current steps on the circuit;
- should be easily integrated in the system.

This required "defined" load behaviour can be realised for a great number of loads by a so-called input circuit for load decoupling.

A possible type of this load decoupling in connection with almost any load is shown in Figure 6.

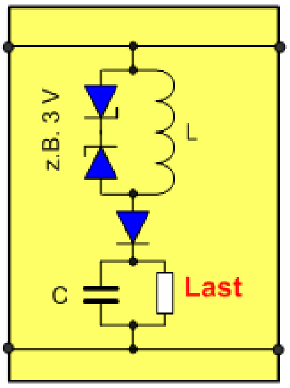

Figure 6. Example of a load with integrated load decoupling

2.7 Quantitative determination of the safety-relevant parameters

Prior to assessing the ignition behaviour of "Power-i" circuits, the typical trace of a make spark in a resistive circuit (basis: IEC 60079-11: 2006 Annex A) must be analysed. Figure 7 shows as an example the real trace of the voltage, current and power of a spark.

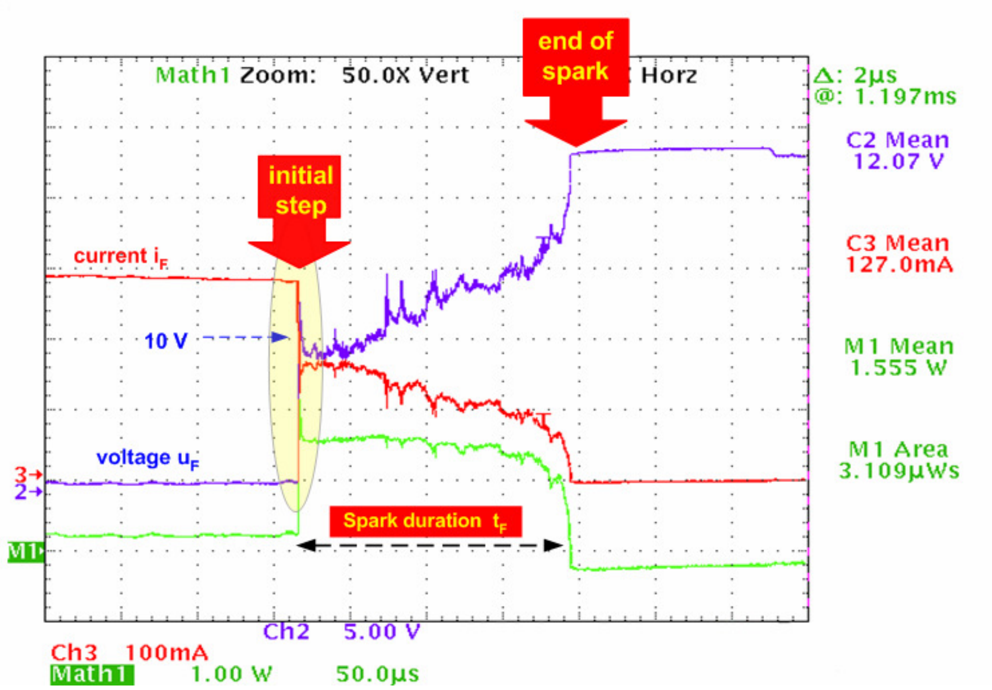

Figure 7. Typical trace of the spark voltage and current of a break spark which is supplied by a linearly limited source

(here: U =24 V and I = 280 mA, spark duration ≈ 180 µs)

These types of break sparks are characterised by the following ignition-relevant parameters (without taking the supply voltage and the supply current used into account):

- ⇒ **the initial step** – each of these sparks causally starts with an initial step; here, the sparking voltage increases in less than 100 ns from 0 V to the value of the sparking voltage loss drop of approximately 10 V; from this, the simultaneous decline of the spark current results.

  (Note: The value for the spark voltage loss drop is valid for the contact mating of the spark test apparatus for tungsten-cadmium; for other contact matings, this value may be higher).
- ⇒ **The regime of the sparking voltage** during the spark duration; this regime is decisive for the effective ignition power consumption**.** Only voltage values above the sparking voltage loss drop of approximately 10 V are capable of causing ignition and provide a contribution to the effective ignition energy;
- ⇒ and **the spark duration** – The spark duration can vary in the case of this type of break sparks from approximately 20 µs to approximately 2 ms! (As for the reason, see above)

The maximum admissible values specified in the IEC 60079-11: 2006 in Annex A are obtained under these basic conditions. As the strongly varying spark duration is directly linked to the possibility of a strongly varying energy consumption in the sparks, this has to be taken into account when laying down the admissible maximum values. This leads to the - in comparison with "Power-i" - relatively small threshold values in the above-mentioned IEC.

It is right here where the basic idea of the "Power-i" safety concept applies. Immediately after the detection of a spark, the safe separation of the load circuit from the energy supply of the source takes place. Due to the separation, the energy supply required for an ignition is withdrawn from the spark. The hardware shutdown times of the power-i sources are usually below 2 µs.

For the safety-relevant analysis, the evaluation of the maximum system-dependent "Power-i" response time is, however, of relevance. This response time can be equated with the maximum shutdown time of the system which is derived from the sum of the hardware shutdown time and the (double) maximum cable propagation time, plus any delays which might be caused by the load. The maximum shutdown time can thus be calculated in advance. For example, for a system according to Figure 5, with a cable length of 1000 m, the maximum "Power-i" shutdown time amounts to approximately 15 µs (2 µs + 6 µs + 6 µs + 1 µs). In contrast to conventionally fed DC circuits, where the spark duration is extremely variable, spark durations of more than 15 µs are definitively ruled out here.

This permits clearly higher admissible threshold values whilst, at the same time, the ignition probability remains the same as in the case of the conventional analysis. Figure 8 illustrates this relationship by means of a real plot. In this example, the reduced spark duration is 13.8 µs.

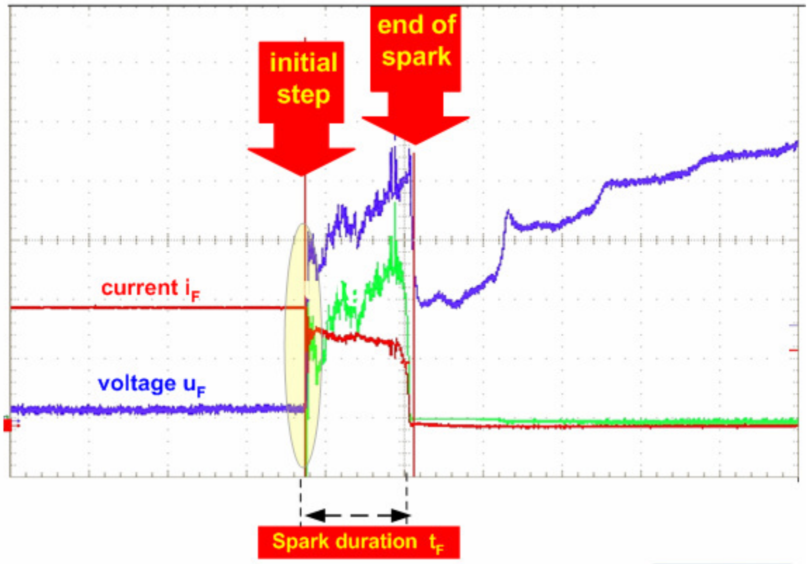

Figure 8. Forced reduction of a break spark by Power-i supply (here: U =24 V / 400 mA, cable length 1000 m, spark duration = 13.8 µs)

2.8 Which effect, from an energetic point of view, does the spark duration reduction have on the ignition behaviour?

Preliminary Note:

In the case of the sparks considered here, mainly two mechanisms of energy distribution are dominant: on the one hand, the specific thermal capacity of the gas mixture, and on the other hand the heat losses. In the case of "long duration" sparks (> 50 µs), the heat losses are dominant. To compensate these losses for a possible ignition, higher power consumptions are necessary. In the case of the "short duration" sparks considered here, these heat losses can be neglected. The power is mainly used to heat up the initial gas volume with its specific thermal capacity.

Figure 9 shows the curve of constant spark energy as a function of the spark power and of spark durations which are not longer than 20 µs. This curve represents the minimum energy value which – minus all energetic losses – is required for an ignition; this value is to be defined as "minimum effective ignition energy" $W_{F\text{-}effective}$. For spark durations below 20 µs, the following simplified approach applies:

$$W_{F-effective} = \int_{initial-step}^{spark-end} P_F\,dt = W_F = W_{F-cons\tan t} \text{ with } P_{F-effective} = P_F = (u_F - 10V) * i_F$$

Ignition tests which PTB carried out with the spark test apparatus yielded for $W_{F\text{-effective}}$ a value of below 10 µJ for explosion group IIC.

Thus, each point on the curve in Figure 9 forms a rectangle with a constant surface area. Related to the energy values W_1 and W_2 which have been plotted in Figure 9 exemplarily, the following applies:

$W_1 = W_2 = W_{F\text{-}constant}$. The figure shows clearly that the required "effective incendive power" $P_F = P_{F\text{-}effective}$ is, in the case of longer spark durations (e.g. $t_F = t_2 = 25$ µs at P_2), considerably smaller than in the case of shorter spark durations (e.g. $t_F = t_1 = 5$ µs at P_1).

The increase in the "effective incendive power" is directly related with a possible increase in the electrical connection values! This effect is applied for the "Power-i"-system.

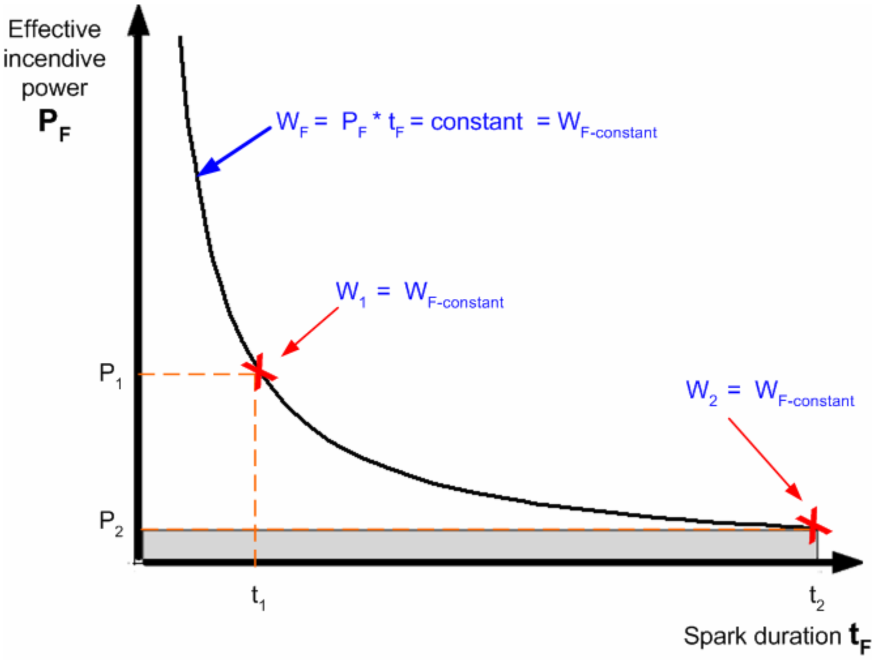

Figure 9. Curve of constant "effective ignition energy" (Schematic diagram for spark durations $t_F < 20$ µs)

In Figure 10, the effective output power attainable in a "Power-i-system" under certain basic conditions was plotted - based on Figure 9 - as a function of the system response time and the cable length. These are qualitatively determined minimum ignition curves based on single values which have been determined by means of the spark test apparatus. (Note: All curves contained in Annex A of the IEC 60079-11 were determined in the same way!)

The value specified for the slewing rate of the spark voltage of 1.2 V/µs is an empirically determined value which was laid down on the basis of numerous measurements carried out by PTB. Smaller slewing rates are uncritical from a safety point of view; the occurrence of higher values can be regarded as negligible under the aspect of ignitability. Similar applies to the cable propagation speed of 160 m/µs. Here, the value is regarded as the minimum value, i.e. a higher speed means more safety. A lower speed is to be subjected to a special consideration.

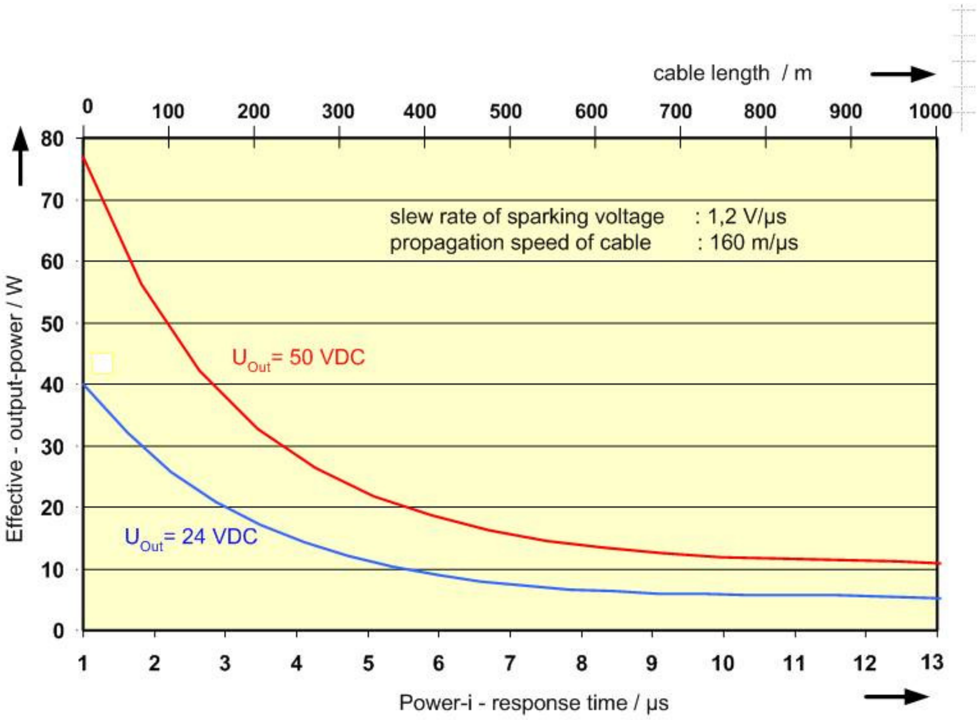

Figure 10: Minimum ignition curve: Effective output power of a "Power-i" source as a function of the system response time and the cable length

2.9 Summarizing consideration for the specification of safety-relevant parameters

The classical assessment procedures for intrinsically safe circuits according to IEC 60079-11:2006, which have been customary up to now, are not sufficient for the evaluation of "Power-i" circuits. The following safety-relevant proof is required:

a) Proof of the maximum system-dependent Power-i response time,
b) Proof of the safe detection of current steps (levels, operating times, etc.);
c) Proof of the safe shutdown (or of the transition to a safe condition) in the case of a failure;
d) Proof that the behaviour listed in a) to c) is not adversely affected by any component of the overall system source + circuit + load.

3 Procedure for testing "Power-i"-systems in practice

3.1 Objective

On the basis of the definition of "Power-i" systems and the information provided in section 2, currently no internationally agreed test procedure exists for proving the ignition capability of

such circuits. The detailed requirements for this purpose are not included in the basic standard of the type of protection "intrinsic safety"- "i", standard IEC 60079-11: 2006.
It is thus the objective to develop a suitable procedure for proving the ignition capability. This procedure should take the special conditions of this type of dynamically reacting electric circuits into account. As a contacting device, the test spark apparatus according to IEC 60079-11 Annex B shall be used. In the future, this novel test procedure is intended to be integrated in the IEC standards.

3.2 Requirements

The new procedure for proving the ignition capability must fulfil the following requirements:

a) The mechanism of spark generation must be based on the spark test apparatus according to IEC 60079-11: 2006 Annex B. By this, the comparability to the threshold values specified in Annex A is guaranteed;

b) To determine the ignition capability (ignition probability) , only those contact makings/breakings shall be used (counted) where the source is in an active operating condition, i.e. the electric output quantities to be tested (U_{Out} and I_{Out}) must be applied verifiably to the contacting device.

c) It should be possible to implement the test procedure as easily as possible;

d) Circuits which have static characteristic curves and could therefore be tested according to IEC 60079-11: 2006 must furnish comparable results with the novel test procedure (within the scope of the uncertainty which can usually be achieved with metrological means).

3.3 Test set-up with Spark Test Apparatus Control Unit (STA-CU)

The requirements specified above can be realised by means of the test set-up illustrated in Figure 11. The core of this set-up is a series box which, in the following, will be called "Spark Test Apparatus Control Unit" (STA-CU). This is a special control and monitoring unit which is connected between the power supply (DUT) to be tested, the spark test apparatus (STA) and the load. The task of the STA-CU is to ensure that only those contact makings/breakings are used for the safety assessment where the source can also supply power to the load, i.e. where the source is active. The basic configuration of the STA-CU is also illustrated in Figure 11.

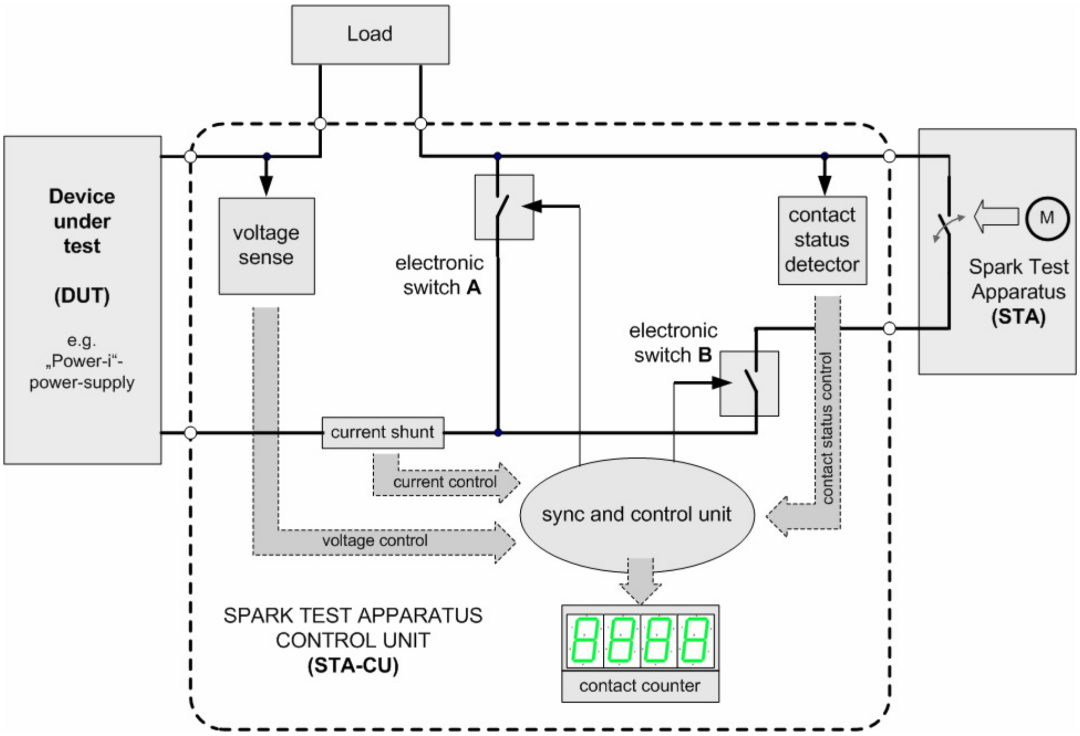

Figure 11. Test set-up with the Spark Test Apparatus Control Unit (STA-CU)

3.4 Application of the Spark Test Apparatus Control Unit (STA-CU)

Before starting any practical test, the values for the normal operating conditions of voltage and current (U_{Out} and I_{Out}) for the DUT must be preset on the STA-CU. Only if these values can be attained during contacting, the contact makings/breakings are considered as being valid and are therefore countable.

It is a known fact that we have to distinguish between two types of contacting, the "circuit interruption (break)" and the "circuit closing (make)“, which work with different mechanisms requiring different methods. For this test, the most ignition-critical type of contact, i.e. the break spark or the make spark, shall be preset at the STACU. If no reliable statement can be made, both types of contact shall be tested.

For both types of contacting, the characteristics of the circuit to be tested are determined at the beginning of the test - independent of the condition of the spark test apparatus.

At first, the no-load test is carried out. For this purpose, it is tested whether the preset voltage (nominal voltage) of the "Power-i" supply (DUT) is really applied (Switch A and Switch B – open). If the voltage is correct, the load test follows, for which the DUT is smoothly connected (by slowly closing Switch A) via the STA-CU to the nominal load. This smooth connection prevents a premature shutdown of the "Power-i" supply (DUT). In this way, the normal operating condition of the test circuit (DUT) is ensured.

Starting from this original state (Switch A - closed, Switch B – open), different test procedures are then realised for the two types of contacting.

Testing for break sparks:

a) When the preset values for electric current and voltage (I_{Out} and U_{Out}) are applied to the load, the checking procedure of the contact position of the spark test apparatus (STA) is carried out. It is only when the contacting device is closed that the STA-CU connects the load current to the spark test apparatus via Switch B (Switch B closed). Subsequently, Switch A is opened and the current flows thus exclusively via the contacting device of the spark test apparatus.

b) The subsequent contact opening of the spark test apparatus thus generates a break spark, which is generated under "real" conditions during normal operation of the source. Now the values for current and voltage (I_{Out} and U_{Out}) that are to be tested are applied here, (see also the range of the "Power-i" characteristic curve in Figure 3).
Only the break sparks generated under these conditions are counted and used for the assessment of the ignition behaviour.

Testing for make sparks:

a) Here, Switch A is "smoothly" opened and, at the same time, the output voltage of the DUT is checked. If the output voltage of the DUT does not decline during this opening of Switch A, it can be assumed that the DUT is in a condition ready for operation.

b) Only when the contacting device of the spark test apparatus is open, Switch B is closed via the STA-CU and the spark test apparatus (STA) is directly connected with the DUT. Now, the operating values for electric current and voltage (I_{Out} and U_{Out}) are applied here. The contacting of the spark test apparatus which then follows thus generates a make spark which occurs under "real" conditions.
A make spark generated under these conditions can be used as countable for the assessment of the ignition behaviour.

3.5 Summarizing consideration of this verification procedure

The application of this verification procedure enables testing and certification stations (test houses) to verify also the ignition behaviour of dynamically reacting intrinsically safe circuits (e.g. "Power-i") in practice. As for all other ignition tests in the type of protection "intrinsic safety", the spark test apparatus is used according to IEC 60079-11 Annex B.
The core of the verification procedure is a series box, the "Spark Test Apparatus Control Unit" (STA-CU), which is to be connected between the load, the spark test apparatus and the device under test (DUT). The STA-CU is a special control and monitoring unit which guarantees that

only those contacts are used for the assessment of a circuit's ignitability whose circuit under test is also in the active mode.

This helps to effectively prevent that the counting of the contact makings/breakings can be continued on the contacting device if the supply unit is shutdown - due to the spark test apparatus connected to the load circuit.

The ignition capability of a circuit determined by means of this verification procedure is thus - with regard to the ignitability - directly comparable with the minimum ignition values which are currently found in the IEC 60079-11:2006.

4 Necessary steps for an implementation in the international standardisation

As the testing technique - and also the standardisation requirements concerning the type and the system configuration - are novel and complex for dynamically active circuits, we suggest to initially integrate this technology in the set of explosion protection standards as a **"Technical Specification" (TS) at IEC**. According to the rules of IEC, a Technical Specification can be published if the technology is still under development or if, for other reasons, there will be the future possibility to achieve an agreement for the publishing of an international standard. The time for drawing up a Technical Specification is significantly shorter than for publishing a normal IEC standard. After sufficient experience has been gained with the TS, it can be transformed into a normal IEC standard, or the content can be integrated into an already existing IEC standard.

Already today, "Notified Bodies" can issue for the European Economic Area EC-Type examination certificates according to Directive 94/9/EG (ATEX) for dynamic sources, e.g. "Power i", which may even deviate from the currently valid standards.

To increase the understanding and the industrial acceptance of this innovative technology, PTB launched a **project** in mid-2009 on the subject "More intrinsically safe active power by dynamically acting circuits - realisation, implementation, testing and placing on the market" (**short title – Power "i"**) which is financed by German industry companies.

5 Conclusion

New approaches together with novel circuit solutions have significantly increased the attractiveness of the type of protection "intrinsic safety". Thus, intrinsically safe active power values can be realised up to 50 W with the dynamically reacting "Power i" concept.

Numerous market participants have agreed on supporting an open standard and interoperability for "Power-i" systems.

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