INNOVATIVE STRATEGIES FOR INTERNAL ARC-FLASH RISK MITIGATION IN LV SWITCHGEARS

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Abstract - Internal Arc Classification (IAC) of Low Voltage switchgear according to IEC and IEEE standards is one of the most important requirements to guarantee personal safety in case of internal arc faults. One of the challenges is to find innovative strategies to reduce damages of arc triggering utilizing more specific solutions inside the switchgear. As known, there are three mains philosophies of Arc Fault Management: *Active protection*, based on monitoring of electrical devices; *Passive protection*, obtained using structural reinforcements and insulations, *Avoidance philosophy*, where the assembly guarantees a reduced risk of arc fault (e.g. the arc ignition protected zone).

What this research is going to explore is the *Passive protection* and the *Avoidance philosophy* with the introduction of new approach for internal arc-flash risk mitigation. The paper presents an innovative validation procedure in order to improve the IAC.

Index Terms — Passive protection, Avoidance philosophy, Internal Arc, Arc Fault Management, Arc Fault protection.

I. INTRODUCTION

NFPA (National Fire Protection Association) Standard 70E [1] defines arc-flash as “a hazardous condition associated with the emission of energy by an electric arc”.

By definition, an arc-flash is an electric arc that occurs unintentionally. In particular, an arc-flash occurs when there is a loss in the insulation between two conductors of sufficient difference in voltage. The presence of an electric arc can therefore be a source of damage or fire, especially in the vicinity of high-power electrical equipment. The short-circuit capacity available is generally very high, as is the energy associated with the resulting arc-flash.

Identifying potential arc-flash conditions has become a very important part of the safety procedures adopted in industrial and domestic electrical systems, especially in integrated systems such as switchgear. Standards and regulations that protect operators from risks of direct contact while working on or near such systems are being drafted. Despite the arc faults and the risks of arc-flash incidents are widely known; the following documents are available only in the USA:

- NFPA 70E [1] (Standard for Electrical Safety in the Workplace) covers all risks of electrical nature, including those associated with arc faults, and specifies the PPE (Personal Protective Equipment) to be adopted according to the risk category;
- IEEE 1584-2002 [2] (Guide for Performing Arc-flash Hazard Calculations) provides methods to be used in calculating arc-flash incident energy and allows for the determination of safe work zones for protection against arc-flash events.

The principal effects of an electric arc considered by the standards are intense heat and light, loud noise and explosive overpressure. The consequent problems are:

- the heat and sprays of molten metal can produce lethal burns;
- the noise produced can cause temporary or permanent hearing loss;
- the arc-flash can cause damage to the eye vision;
- the explosive overpressure can open and unhinge the doors of switchgear assemblies and cause people working at heights to fall.

In addition to human injuries, the electric arc can cause serious damage to electrical equipment and trigger power outages in electrical systems in industrial plants and in the building sector at considerable service costs, sustained by huge system downtime.

Therefore, risk management and prevention is becoming an essential part of the safety program in the electric power sector, because the correct evaluation of arc-flash risk levels can help to reduce system downtimes and ensure safer work conditions. It must also be noted that present standards do not provide an evaluation method of arc fault risk, so *Active protections* (detection systems and switches capable of breaking fault currents) are mainly adopted.

In order to use *Passive protections* and *Avoidance philosophies* it is necessary to design the arc fault zone, and the knowledge of electric arc behavior is essential. Literature provides various models for use, see [3], [4], [5], [6], [7], [8]. These models are macroscopic representations of the arc phenomena that provide information that may prove useful in applying the best strategies to both reduce the probability of arc fault occurrence and to limit its effects.

A description of the electric arc behavior for a better understanding of arc-flash phenomena will be provided below.

II. VARIOUS ARC FAULT PROTECTION PHILOSOPHIES

Protection against the effects of an arc fault in low-voltage switchgear can be provided in various ways.

It has become consolidated practice to group these approaches to protection by the philosophies below: literature refers to *Active protection*, *Passive protection*, and *Avoidance protection*.

All the solutions in which the switchgear is monitored by a system comprising electric and electronic components capable of detecting the fault and triggering the intervention of protective equipment are grouped under *Active protection*.

Therefore, *Active protection* technical solutions include control, protection, and intervention systems.

Alongside traditional systems composed of protective equipment such as circuit breakers or disconnect switches and controlgear including transformers and relays, monitoring systems, consisting of infrared sensors for temperature measurement and optical sensors capable of detecting the light generated by an electric arc, are currently required. The optical sensors can be either point detectors or made in continuous optical fiber: as it will be illustrated below, both systems have their strengths and weaknesses.

Because limiting the damage caused by the development of an arc fault may be considered *a question of time*, the use of light-sensitive sensors is preferable in the realization of an efficient protection system.

These sensors must naturally be provided with an equally rapid data transmission for the shortest response times possible.

In contrast to than Active protection, the objective of *Passive* switchgear *protection* is the containment of the electric arc and its effects.

Because safety is such an essential part of the standards, particularly those of Europe, should an electric arc ever form, the switchgear's structure and enclosures must be capable of containing the explosive overpressure, incandescent gases, and violent ejection of material.

This measure guarantees the safety of the personnel, while practical interventions on the switchgear, such as structural reinforcement, the use of door/hinge blocks, the creation of ducts or vents for the discharge of the gases and the insertion of insulation barriers are the solutions adopted for *Passive protection* for switchgears.

Together with the measures taken for the switchgear structure, PPE (Personal Protective Equipment) provides personnel with *Passive protection* against arc fault events.

The third, the *Avoidance* approach or *philosophy*, is based on designing switchgear in such way to ensure that an arc-flash cannot occur.

In other words, the presence of insulation or segregation barriers with a high degree of protection inside the switchgear allows the manufacturer to define all or only certain compartments of the switchgear cubicle "arc ignition protected zones" with consequent protection guaranteed by the impossibility of arc fault occurrence.

The following additional observations are worth making before proceeding to an analysis of each solution's strengths and weaknesses.

Both *Active protection* and *Passive protection* are subjected to validation by laboratory tests that guarantee their correct functioning.

To this end, the European standard [2] and the United States standard [9] provide useful information for *Active protection* and *Passive protection* (design, construction, and testing of switchgear protected against faults that trigger arc-flashes), while when an *Avoidance protection* design solution is adopted, current standards offer no design validation instruments, and this makes the "arc ignition protected zone" a "weak" solution because it is not supported by experimental evidence.

Therefore, the identification of instruments capable of permitting the validation of this protection approach, assumes fundamental importance.

III. STRENGTHS AND WEAKNESSES OF THE VARIOUS SOLUTIONS

After providing an overview of the context in which switchgear equipped with internal arc protection is designed and constructed, a brief analysis of the advantages and disadvantages offered by each system of protection should be made.

Active protection systems, especially when the monitoring systems employ optical sensors, offer the advantage of providing very rapid arc fault detection times with an accuracy of a millisecond.

After this, almost instantaneous, detection the protection relay sends command to the protective devices to disconnect the power supply and eliminate the fault.

As described above, optical sensors can be either point detectors or made in continuous optical fiber.

Although point detectors are easier to install, they can only monitor a limited volume, meaning that higher numbers of sensors must be installed in each switchgear compartment.

Continuous optical fiber sensors permit wider monitoring on the other hand, but they are much more difficult to install. Furthermore, the length of the continuous fiber to be installed is limited by the loss of the signal, and this could prohibit its use in switchgears with many compartments.

It must also be remembered that despite their nearly instantaneous reaction times, damage caused by the formation of an arc is not precluded instantly, due to the fact that the optical signal must always be processed by the monitoring system before that the protective device is commanded by this system to make a circuit breaking manoeuvre (UK).

The signal processing time is usually around 10/30 ms, whereas owing to their electro-mechanical mechanisms, the protective devices that nearly always consist of switchgear of a large size and capacity have manoeuvre (UK) times in the order of 50/100 ms.

As short as it may be, the total intervention time is long enough for electric arcs to cause often quite serious damage to the compartment.

The economic aspect must also be borne in mind: monitoring and control system equipment can be expensive, and its installation and maintenance particularly so. Damaged sensors can be very costly to replace, and a malfunctioning continuous optical fiber sensor can break the circuit, leaving a large part of the switchgear unmonitored.

Passive protections, or rather structural reinforcements, door blocks, and all the other solutions described above offer the advantage of requiring no maintenance or monitoring.

Adopting higher and higher arc current protection values (typical rated values are 50kA, 70kA, 100kA, up to 150kA) cannot, however, be obtained by increasing *Passive protections* indefinitely.

Enhancing structural reinforcement, the thickness of the plating, and the insulation and segregation barriers results in excessive increases in both switchgear dimensions and production and assembly costs.

Continuing along these lines ultimately raises the risk of producing a product that is no longer economically competitive.

In accordance with above, the *Avoidance protection* appears the most interesting. Indeed, the design of switchgear with "arc ignition protected zones" offers the advantage, in theory, of reducing arc fault risks to zero. In practical terms, this means eliminating the costs required for intervention and replacement following a fault and, in any case, reducing equipment maintenance costs.

On the other hand the absence of a regulatory procedure that certifies that a compartment or a part of it is an “arc ignition protected zone” amounts to a serious drawback due to the fact that such protection remains based on an assumption that cannot be demonstrated and it is for such reason debatable.

In conclusion, when designing switchgear, the use of the various solutions must be assessed carefully, and a correct balance of strengths and weaknesses, benefits and costs must be reached without lowering the level of safety for personnel (an objective that must not be compromised for any reason whatsoever).

IV. EXAMPLE OF PROTECTION MODE: EXPLOSIVE ATMOSPHERE

It is useful to point out that some of the protection solutions previously described are also used in other industrial environments so it could be possible to adopt the same protection strategy and protection validation.

One of the main interesting and dangerous industrial environmental is Ex environment, such as Oil&Gas field where an explosive atmosphere could be often present.

An explosive atmosphere is a mixture of flammable substances in a gaseous, foggy, vaporous state, or powder mixed with air, under certain atmospheric conditions in which, after ignition, the combustion propagates itself to the flammable mixture. A potentially explosive atmosphere is only obtainable if the concentration of the flammable substance is not too low (lean mixture) or too high (rich mixture): in these cases, a combustion reaction may occur, or even no reaction at all, but no explosion.

In order to avoid an explosion, it is mandatory to limit one of this three elements: fuel, combustive agent (oxygen) and an ignition source. Therefore, an explosion cannot occur if even just one of these three elements is not present, as shown by the explosion triangle of Fig. 1.

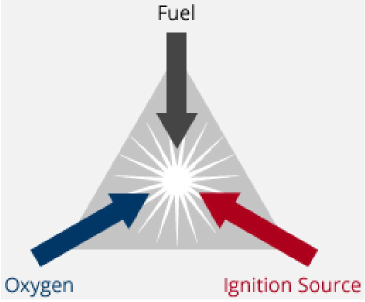

Fig. 1 – The explosion triangle.

Therefore, three different principles, which act differently on these three elements of the triangle can be implemented to be safe the electrical equipment. These three different principles are:

- *containment method*, the parts that can cause ignition are included in a box made to withstand the pressure of the explosion, preventing the spread of flame;
- *prevention method*, in this method necessary measures are taken to avoid excessive temperatures and creation of sparks, thus eliminating the ignition source;
- *segregation method*, in which active components are separated from explosive mixture using resins, sand, oil, preventing any contact with oxygen and fuel.

All the protection modes for Ex environment, as described in [10] for luminaries, born from these three different principles and it is possible to compare these protection solutions used for explosion atmosphere to the protection solutions adopted against the effects of a fault with the formation of an electric arc.

The *Passive protection*, used for Low Voltage Switchgear, has the aim of containing the electric arc and its effect, as for the *containment method* used in Explosive Atmosphere. The related mode of protection is called “Ex d” and the parts which can ignite a potentially explosive atmosphere are surrounded by an enclosure which withstands the pressure of an explosive mixture exploding inside the enclosure itself, and prevents the transmission of the explosion to the external atmosphere surrounding the enclosure [11]. Obviously, a correct design of the flameproof joint and the enclosure (thickness) is mandatory as well as the positive result of the type tests according to IEC 60079-1 [12]. It is very important to design the length, the gap and rugosity of the joint between cover and body of enclosure according to the Standard.

The philosophy of *Avoidance protection*, used for Low Voltage Switchgear in order to avoid the arc-flash effect, is based on the design of the switchboard to ensure that a failure cannot occur, as per the *prevention method* used in explosive atmosphere. The related mode of protection is called “Ex e”, where additional measures are applied to the electrical equipment to increase the safety level, thus preventing excessive temperature development and the occurrence of sparks or electric arcs within the enclosure or on exposed parts of electrical apparatus, where such ignition sources should not occur in normal service [11]. Obviously, a correct design of the insulation distance (creepage and clearance) according to the material used and the electrical parameters is mandatory as well as the positive result of the type tests according to IEC 60079-7 [13].

Differently, there is no an equivalent mode of protection, used in explosive atmosphere, like the *Active protection*, used for Low Voltage Switchgear in order to avoid the arc-flash effect because the arc-flash has an high temperature and an high ignition energy that can be the ignition source itself.

In Ex design the minimization of the probability of arc ignition is a very important strategy that at the moment is not a IEC Standard yet. This minimization can be done by calculations or by practical tests.

By calculations, to minimize the probability of the arc ignition, it is possible to evaluate the causes of failure and the failure rates of each component suitable for protection (SIL - Safety Integrity Level). Comparing it with the hours of possible presence of the explosive atmosphere (depending on the danger zones), it is possible to check whether the installation is suitable or not [14].

By practical tests, it is necessary to define the right approach to follow and to spend money both for prototypes and to execute destructive laboratory tests.

V. THE ELECTRIC ARC

Many electric arc models have been developed: microscopic (particle physics) and macroscopic (thermal, dynamic and electric). The macroscopic electric models that describe the arc’s behavior in a circuit are enough for the study of the arc-flash. These models include the well-known Ayrton Model [15] , the Mayr Model [16] and the

Cassie Model [17]. Using the Ayrton Model on which the others are based, it may be observed that in strictly electrical terms, an electric arc can be represented as a useful resistance R_U (having the nonlinear characteristic) shown in Fig. 2.

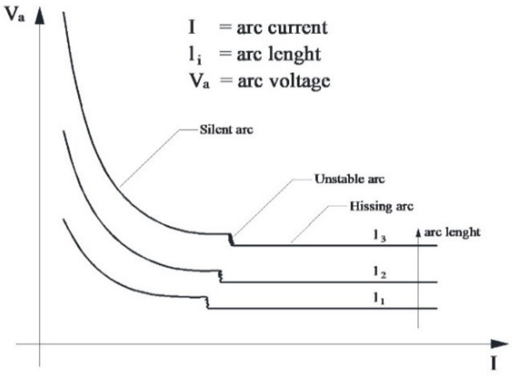

Fig. 2 - Volt-amperometric characteristic of the electric arc

Fig. 2 shows how the arc characteristic is anomalous: with modest current values: the apparent resistance $r = \frac{V_a}{i}$ decreases as the current i increases, whereas with very high current values, not represented in Fig. 2, it begins to rise in the same way as "normal" resistance. Between these two zones and for high current values in any case, the arc voltage V_a instead remains practically constant. This can be explained by imagining that as the current i increases, the section of the ionized region through which the current passes increases and at the same time, the state of ionization increases (or rather, the resistivity of the conductor decreases).

On the Cartesian plane in Fig. 2 with the current absorbed plotted on the x-axis and the arc voltage on the y-axis, for a determined arc length value, an electric arc can be divided into three zones:

- *silent arc*: where V_a decreases notably as i increases. For this zone of the characteristic, Ayrton's formula can be applied:

  $$V_a = A + B \cdot l + \frac{C + D \cdot l}{i} \qquad (1)$$

  where *A*, *B*, *C* and *D* are positive constants that depend on the diameter and physical nature of the electrode and the gaseous interposed, and *l* is the arc length;
- *unstable arc*: in which the arc is intermittent and unstable;
- *hissing arc*: in which V_a remains practically constant with the variation of *i* notwithstanding its variation with the variation of the arc length. In this zone, the first binomial of the equation (1) is valid with the expression as follows:

  $$V_a = A + B \cdot l \qquad (2)$$

An examination of the arc characteristics in Fig. 2 shows how in the first section, a decrease in arc voltage is followed by an increase in the current value: this zone section possesses a negative differential resistance, demonstrating the unstable nature of this phenomenon.

Even if formulas (1) and (2) are valid only for a limited range of current, and such limit is usually reached quickly when an arc-flash occurs, learning the principal parameters that govern the electric arc's behavior allows for the implementation of all the counter-measures that can reduce the probability of ignition.

Analyzing the electric arc's current and voltage waveforms is also helpful in acquiring a better understanding of the phenomenon. As will become clearer below, in reality, the anomaly of the arc characteristic is such that the electrical quantities in question are not sinusoidal in development.

Hypothesizing a sinusoidal arc current waveform *i*, V_a would take the waveform shown in Fig. 3.

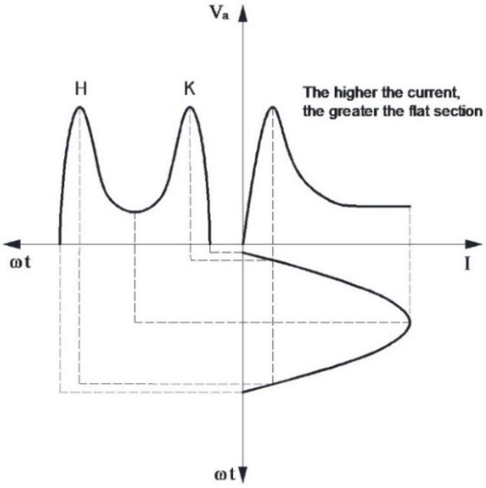

Fig. 3 – Characteristic of an electric arc with a sinusoidal current flowing through it.

In reality, arc hysteresis phenomena are such that V_a is not symmetrical. This can be seen in Fig. 4, where point H is lower than point K.

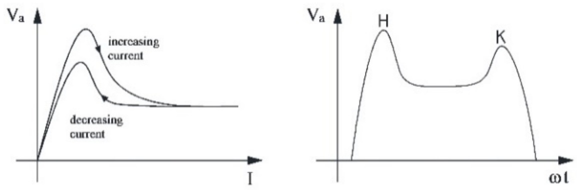

Fig. 4 - Characteristic of a real electric arc.

Based on the above, or rather, that the arc voltage V_a may be considered constant to a fairly good degree of approximation, an electric arc can be represented as a square wave voltage generator of constant amplitude V_a with the variation of the arc current, as shown in Fig. 5, and as a function of only arc length *l*.

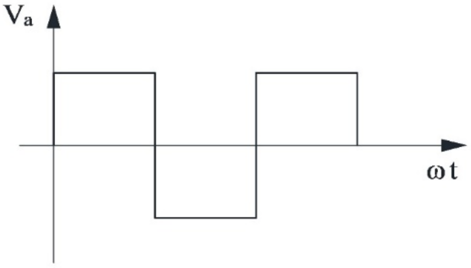

Fig. 5 – Representation of an electric arc by square wave.

Starting from an equivalent electrical circuit model for the electric arc shown in Fig. 6 in which the power supply network is hypothesized as having infinite power, the input voltage is sinusoidal and the source impedance is purely inductive because in general the X/R ratio is higher than 5.

In the circuit shown in Fig. 6, the arc was represented by a square wave generator of amplitude V_a. Even if not stated appropriately, the arc voltage may be said to be in phase with the arc current *i*, in the sense that it inverts its sign when it crosses the current's zeros.

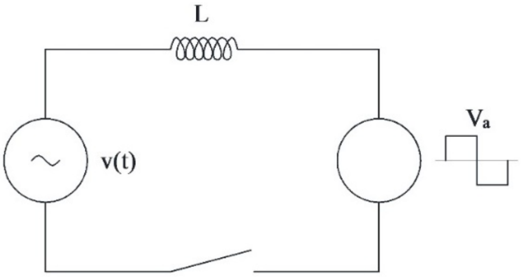

Fig. 6 – Equivalent electric circuit of an electric arc represented by a square wave generator.

When the circuit shown in Fig. 6 is connected to the supply in the moment t=0, the arc cannot ignite before $\omega \cdot t=\varphi_1$ because as shown in Fig. 7 the input voltage $v(t)$ equals V_a only in this moment.

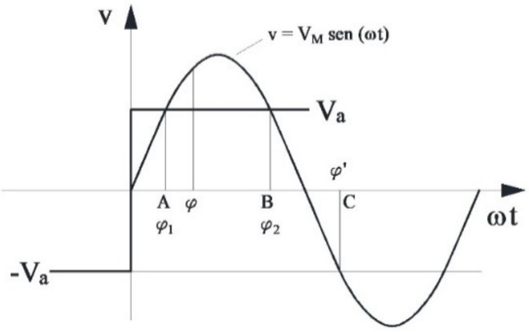

Fig. 7 - Electric arc arcing conditions.

In the circuit in question (prevalently inductive in nature), the first current rise in the electric arc current can take place only with an angle $\varphi \geq \varphi_1$. This means that Ohm's Law can be applied to the circuit, assuming the moment in which the current crosses zero as the starting time. In this way, the starting time for the sinusoidal supply voltage is expressed by:

$v(t) = V_M \cdot \sin(\omega \cdot t + \varphi)$

Assuming that the initiation of the electric arc takes place in any moment $\varphi > \varphi_1$, the voltage V_a shifts by φ in regard to $v(t)$, as shown in Fig. 8.

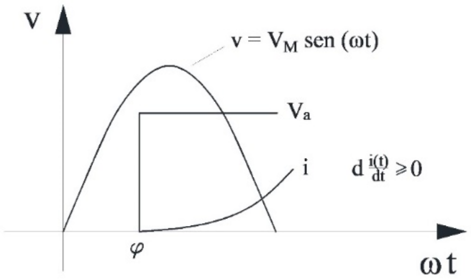

Fig. 8 – Initial behavior of the arc current.

The mathematical relationship obtained by applying Ohm's Law to the circuit in question is:

$v(t) - V_a = L \cdot \frac{d}{dt} i(t)$

Expanding this expression and inserting as initial working condition i(0)=0 allows the arc current to be represented as follows:

$i(t) = -\frac{V_M}{X} \cdot \cos(\omega \cdot t + \varphi) - \frac{V_a}{X} \cdot \omega \cdot t - \frac{V_M}{X} \cdot \cos\varphi$

where $X = \omega \cdot L$. The expression obtained above, at constant φ and V_a, which inverts its sign at every current zero crossing $i(t)$, expresses the non-sinusoidal periodic variation law of the current, which does not have a sinusoidal wave form and can be broken down into a fundamental component and into odd-order harmonics. In particular, the first term is sinusoidal; the second is a straight line passing through the x- and y-axis origin, and the third is a constant term.

From the above, it is clear that if the arc voltage V_a is higher than the peak value of the mains voltage V_M, the arc ignition is impossible.

Moreover, it is worth noting that even if the arc current may not necessarily ignite also with lower arc voltage values, most certainly with arc voltage V_a values of less than or equal to 0.537 of the mains voltage V_M, the arc current would be continuous and re-ignite at each cycle.

Largely similar conclusions would be reached by removing the hypothesis R=0 in the circuit shown in Fig. 6.

VI. A NEW APPROACH

There are clearly substantial differences between the *Active*, *Passive*, and *Avoidance approaches* to arc fault protection in designing equipment.

The concept forming the basis of *Active* and *Passive protection* is that because the arc-flash has already developed following a fault, the objective set for *Active* or *Passive protection* is to limit the damage.

We have seen that *Active protection* is costly and requires reliable control systems. *Passive protection* systems propose solutions that concern the structural sturdiness of the compartment where the arc-flash occurs.

It might be more interesting to succeed in adopting structural measures required not merely to provide passive resistance to arc-flash effects but influence the potential initiation and duration of the arc-flash itself instead.

Currently, only Standard IEC TR 61641 [9] specifies the methods of execution of a test suited to the validation of a *Passive protection* and a procedure for the validation of an "arc ignition protected zone".

The two processes are separate. For *Passive protection* validation, a practical test under arc-flash conditions is run. *Avoidance protection* is validated by means of experimental measurement of dielectric strength (the test voltage value is specified in IEC 61439-1 [18] on the basis of the device's rated voltage) and checking the degree of protection (IP) in accordance with Standard IEC 60529 [19].

In this paper, the authors intend to explore the *Avoidance protection* approach in an attempt to find a new viewpoint from which it may be validated because the test voltage value adopted for the validation of the *Avoidance protection* mode above is the same for a wide range of rated voltages for devices (from 300V to 690V, the test voltage is 2835V).

As presented in Section V and through acquired experience, it has been found that the device's rated voltage is a fundamental factor that affects the potential initiation and duration of the electric arc.

It is useful to specify that in this protection mode, *Passive protection* and *Avoidance protection* can be combined in a new approach.

In line with the new strategy that can be proposed also for a designed area such as an "arc ignition protected zone", the validation process must include a test under arcing conditions that is usually conducted for the validation of at least *Passive protection*.

Conducting experimental tests at the end of the design process of an “arc ignition protected zone” allows for the validation of its utility in establishing whether or not the arc ignited during the test phase proves stable and capable of re-ignition.

This requires the assessment of the factors that influence the life of the electric arc and the way in which it is possible to induce the arc generated during the device test phase to extinguish itself before the end of the test.

As reported in Section V, the parameters that influence the phenomena are input voltage (V_M), arc voltage (V_a), arc resistance (r) and the length of the arc (l) itself.

Obviously because no intervention can be made on the maximum mains voltage value V_M, which is a design value of the switchgear and the arc resistance r value cannot be directly adjusted, attention must be focused on the value of the arc voltage V_a and the arc length value l must be modified.

The choice of materials, their form and position, must therefore be assessed during the design phase, and the protections for the conductors must be designed on the basis of these parameters in order to achieve the two fundamental objectives of this new approach:

1. make the arc length as long as possible i.e. maximize the value of V_a;
2. resist, even if for a limited period of time, during the overtemperature near the arc, in order to prevent it from finding a direct path of re-ignition between the two conductors.

At the end of the design phase, an experimental validation procedure like the one described below must be introduced.

The first step in the validation procedure is to execute the tests indicated in Standard IEC TR 61641 [9] in order to verify the “arc ignition protected zone”.

As indicated above, the Standard specifies only a high voltage test at a voltage value of 2835V for switchgears with rated operational voltages in the range of 300V and 690V.

Given that the operational voltage value influences the duration of the electric arc, the previous test can only be considered necessary, but not sufficient to guarantee that the zone designed is really an “arc ignition protected zone”.

Whenever a fault with the ignition of an arc-flash occurs inside a switchgear, there are three possible scenarios:

1. the electric arc does not propagate inside the “arc ignition protected zone”;
2. the electric arc propagates inside the “arc ignition protected zone” and this prevents re-ignition by extinguishing it before the end of the test;
3. the electric arc propagates inside the “arc ignition protected zone” but this cannot prevent re-ignition and the electric arc is interrupted only at the end of the test.

The occurrence of any one of these scenarios depends directly on the maximum operational voltage value V_M. For this reason, it may occur that after the switchgear has been validated by following the procedure specified in Standard IEC TR 61641 [9], an arc fault test conducted at 300V voltage causes the effect described in point 1, and a fault test at 690V causes the effect described in point 3.

In regard to the above, an “arc ignition protected zone” may be considered as such only after experimental validation, that includes a test under arcing conditions at a precise operational voltage value.

A zone inside the switchgear may be defined an “arc ignition protected zone” only after this practical test has been conducted and provides the outcome described in point 1 (the electric arc does not propagate inside the zone) or in point 2 (the electric arc propagates inside the zone and extinguishes itself before the end of the test). Therefore, the zone can be defined an “arc ignition protected zone” only for values that are lower than or equal to the test voltage adopted during the test.

VII. A PRACTICAL EXAMPLE

For the sake of completeness, a real example of when this procedure was adopted is provided below.

A laboratory test was conducted in Motor Control Center configuration under arcing conditions with the characteristics below:

• rated operational voltage (U_e)	415V
• permissible current under arcing conditions	65kA
• permissible arc duration	0.5s

As shown in Fig. 9, one of the most critical zones, the busbar system, was designed and indicated by the laboratory observer as an “arc ignition protected zone”.

The tests envisioned by the standards for dielectric integrity were then performed at the voltage value 2835V (the value specified for switchgear assemblies with rated operational voltage in the range of 300V to 690V) were conducted and the assembly passed the test with positive result.

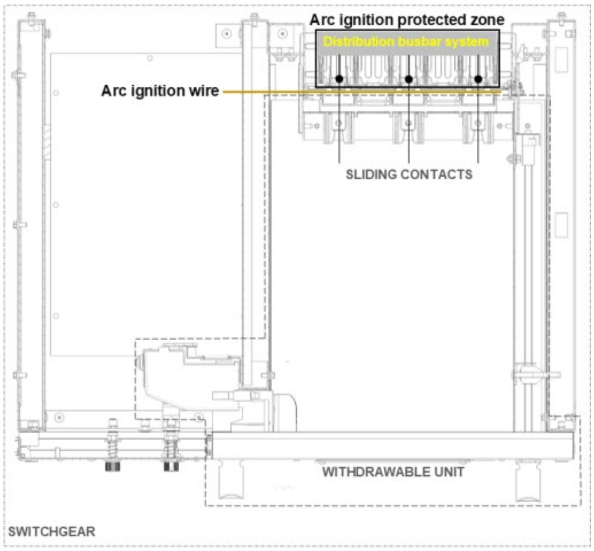

Fig. 9 – Arc ignition protected zone into tested switchgear and arc ignition wire

Fig. 9 shows the busbar zone inside the switchgear indicated to be the “arc ignition protected zone”.

Validation continues by subjecting the switchgear assembly to a practical arc resistance test by inserting a test wire directly between the switchgear’s active elements. Although the internal arcing test cannot not be conducted in the “arc ignition protected zone” by inserting the test wire directly in between the busbar system’s conductors, it is possible to insert such wire in points at the edges of the “arc ignition protected zone”. In this case, the test wire was inserted on the connection clamps of the busbars of a removable unit as shown in Fig. 9 (which shows the position of the test wire insertion in the switchgear ready for the internal arcing test).

From this position, the electric arc can propagate to the busbars and therefore there is no guarantee that an arc sparked in a point in the switchgear outside the “arc ignition protected zone” will not enter.

For this reason, attention should be turned to the influence that this protected zone may have on the behavior of the electric arc.

An initial test was conducted at switchgear with a rated operational voltage of 415V. As expected, once the arc sparked, it moved to the “arc ignition protected zone”. The waveform recorded during the test provided in Fig. 10 shows that the arc currents of all three phases (I_1, I_2 and I_3) cancel each other out after around 180ms. This means that the busbar zone (defined “arc ignition protected zone”) exhibited preventive behavior in inducing the extinction of the arc and preventing its re-ignition. The outcome is the one detailed in point 2 of Section VI above (the electric arc propagates inside the zone and extinguishes itself before the end of the test).

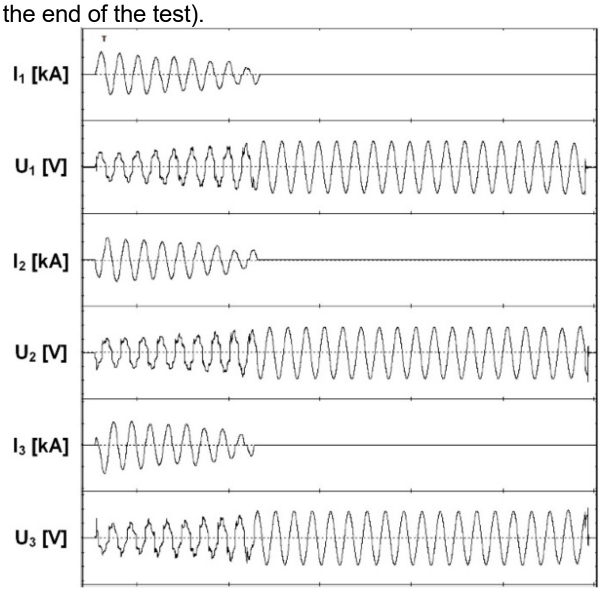

Fig. 10 – result of oscilloscope test at 415V

The same test was conducted also at the different switchgear rated operational voltage of 690V with a short-circuit capacity similar to the case above.

In this case as well, the arc propagated to the busbars, but this time, the spontaneous extinction of the electric arc between all the phases did not occur. This can be seen in Fig. 11, which shows the arc voltage and current values in the three phases. The outcome obtained is therefore the one described in point 3 of Section VI (the electric arc propagates inside the zone and does not extinguish itself before the end of the test).

The two different behaviors obtained depended on the different operational voltage value used during testing. According to the findings, the “arc ignition protected zone” influenced the electric arc’s probability of initiation and duration in the first test but not in the second one.

For this reason, the proposed new strategy is to design protections in such way that ignition is impossible - as indicated by the *Avoidance protection* method philosophy - and then to proceed to a functionality validation by laboratory testing in the same way as for *Passive protections*.

Analysis of the tests’ results may lead to the definition of rules to be shared when designing arc ignition protected zones that ensure correct behavior even when an arc ignites despite the protective measures adopted.

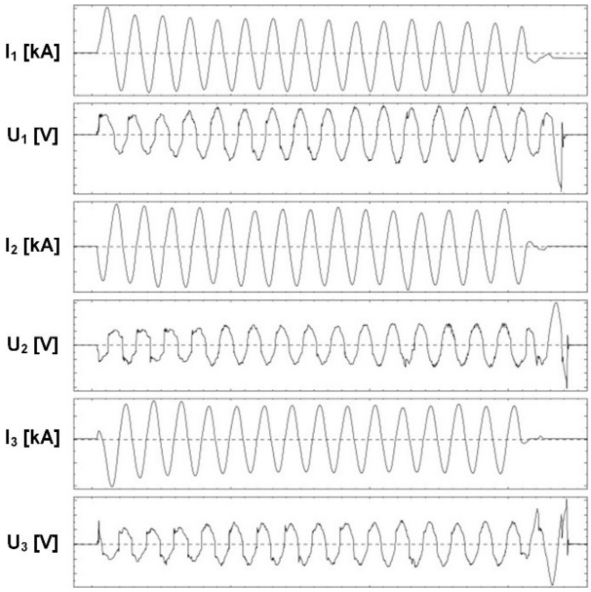

Fig. 11 – result of oscilloscope test at 690V

VIII. CONCLUSION

The final design of switchgear assemblies usually incorporates *Active*, *Passive*, and *Avoidance protection* solutions. While being able to understand the effectiveness of *Active* monitoring and control systems and the *Passive protections* associated with the structures capable of providing protection and containing arc-flash effects is within our possibility, demonstrating that any given zone of a switchgear can be defined “zero risk” is more complex.

Due to the fact that priority in design is generally given to safety, with which degree of certainty can we define a device as “zero risk” and assume all responsibility in that regard?

This paper attempts to clarify the differences between the *Active*, *Passive*, and *Avoidance* approaches to *protection*.

The authors have explored the *Avoidance protection* approach and establish a new viewpoint from which it may be validated.

Succeeding in adopting structural measures (hence those associated with *Passive protection*) required not merely to provide passive resistance to arc-flash effects but which influence the probability of the initiation and duration of the arc itself instead appears very interesting.

The *Avoidance protection* approach to design is therefore entirely different because it requires the assessment of the factors that influence the initiation and duration of the electric arc and the way in which it is possible to induce arc self-extinction or even prevent its ignition.

The choices of the materials, their form and position, therefore become very important for obtaining good results that can be supported by adequate experimentation.

The paper presents a practical method of analysis that may permit switchgear zones to be qualified as “arc ignition protected zones”, and describes the result obtained on the basis of the outcomes of a real practical test conducted on a switchgear.

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