Arc Flash Risk Assessment Using Methodology FMECA

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Abstract— **Paper deals with the Arc Flash Risk Assessment using methodology FMECA (Failure Mode Effects and Criticality Analysis). The aim of this paper is to develop a consistent 4-step model for an arc flash risk analysis and discuss the standard IEEE 1584™-2002 and the technical report BGI/GUV-I 5188 E (German Social Accident Insurance e.V. (DGUV)) used for action in the appraisal of potential thermal hazards due to electric fault arcs associated with electrotechnical work on electrical equipment. Calculated arc or incident energy is one of main inputs of the Arc Flash Risk Assessment. For the calculation based on the above mentioned methods was designed a computer program which was implemented in a programming language C++.**

Keywords—Arc Flash Risk Assessment, IEEE 1584™-2002, NFPA 70E 2015, BGI/GUV-I 5188 E, EN 50110-1 ed. 3, Risk matrix, FMECA

I. Introduction

An arc flash (also called flashover) is part of an arc fault, a type of electrical explosion or discharge that is the result of either a low impedance connection from air to ground, or another voltage phase in an electrical system. Aim of this paper is so to describe and implement calculation methods described in the standard IEEE 1584™-2002 and in the technical report BGI/GUV-I 5188 E and propose a novel model for arc flash risk analysis.

II. Calculation of Arc and Incident Energy

Arc Flashes can have the following severe consequences: 1.) the thermal impact, 2.) a shockwave due to rapid air expansion, which may eject shrapnel outward, 3.) high-intensity electromagnetic radiation, 4.) damage due to the high volume of the sound wave, 5.) the release of poisonous gases as well as particles of materials. Which effects will actually materialize and to what degree is primarily dependent on the amount of energy involved in an arc flash. The impact of electric fault arcing is, for this reason, determined primarily by the electric arc energy W_{LB}. Electric arc energy identifies the relationships with the system short-circuit-related arcing. Different network conditions will result in different electric arc energies. A parameter known as the incident energy E provides a clear measure of the direct thermal impact of an electric arc on the exposed surface of the skin. The unit of the incident energy is J/cm². A successful test will verify that the PPE is arc resistant (AR) and provides protection up to the level of the incident energy E, as per the test settings. PPE are tested under certain circumstances according to IEC 61482-1-2 (Box test) or IEC 61482-1-1 (Open Arc test).

The procedures described in the technical report BGI/GUV-I 5188 E are applicable for the box test method. When selecting the PPE in accordance with IEC 61482-1-2 (Box test) than the thermal hazards associated with electric arching are deemed covered if $W_{LB} \leq W_{LBa}$ applies where W_{LBa} is equivalent arc energy (see as well below). Open Arc test results (IEC 61482-1-2) lead to the so called "Arc Thermal Performance Value (*ATPV*) or Breakopen Threshold Energy (Ebt50)". The known value of the incident energy $E_{i(IEEE)}$ calculated on the basis of the standard IEEE 1584™-2002 is used to select the appropriate PPE, which has to have an equal or higher Arc Thermal Performance Value than the value of the expected incident energy i.e. $E_{i(IEEE)} \leq ATPV$.

There is a non-linear relationship between electric arc energy W_{LB} and incident energy E_i. The link between electric arc energy and incident energy E_i is known for both protection classes for the PPE Box test.

TABLE I.   Box Test Parameters

IEC 61482-1-2 (Box test)	Statistical mean value	
	Electric Arc Energy (W_{LB})	*Incident Energy (E_i)*
Class 1	158 kJ	13,5 J/cm²
Class 2	318 kJ	42,3 J/cm²

It should be noted that incident energy values E_i, which identify the Box test classes, do not correspond to the *ATPV* values, which are determined in tests according to IEC 61482-1-1 or in algorithms according to IEEE 1584™-2002.

Electric arc energy W_{LB} is defined as:

$$W_{LB} = \int_0^{t_k} u_b(t) i_b(t) dt = P_{LB} t_k \qquad (1)$$

where $u_b(t)$ is the arc voltage, $i_b(t)$ is the arc current, t_k is the duration of arcing and P_{LB} is the electric arc power which is dependent upon the maximum short circuit power $S_{k3}^{"}$:

$$P_{LB} = k_p S_{k3max}^{"} \qquad (2)$$

where k_P is normalized arc power which is the function of the rated voltage U_n, the arc voltage U_b and the R/X ratio of the fault circuit impedance. Whereas the arc voltage U_b is expressed

by the empirical equation whose variables are the electrode gab d (distance between system conductors (busbars)) and the rated voltage U_n. Worst-case examinations can be calculated using the maximum value k_P in that case $k_{Pmax}=0,29/(R/X)^{0,17}$.

The equivalent arc energy W_{LBa} is the protection level afforded by the PPE for the respective distance a. It is determined by the test level for the PPE (Class 1 (W_{LBP}=158 kJ), Class 2 (W_{LBP}=318 kJ)), working distance a (the distance between the electric arc and the person's body) in mm and the transmission factor k_T (defines the system configuration and describes the spatial propagation of the electric arc thermal impact in the space):

$$W_{LBa} = k_T \left(\frac{a}{300}\right)^2 W_{LBP} \qquad (3)$$

The duration of arcing t_k is dependent upon the actual settings of the tripping curve of the respective protection device and the actual arcing fault current I_a which is significantly lower than the calculated short-circuit current $I_{k3}^{''}$ at the fault location due to the finite size of the arc impedance. The electric arc cannot be determined in certainty. Essentially, this empirical equation is applicable:

$$I_a = k_b I_{k3min}^{''} \qquad (4)$$

where $I_{k3min}^{''}$ is minimal short-circuit current and k_B is the current limiting factor which is the function of the type of the arcing fault current (three or two pole arcing fault current) k, the rated voltage U_n, the arc voltage U_b (definition see above) and the R/X ratio of the fault circuit impedance. If one assumes k_B=0,5 and uses this reduced current to determine the tripping time from the tripping curve of the respective protection device it is generally considered to be safe. In compare to (4) the arcing fault current $I_{a(IEEE)}$ defined in the standard IEEE 1584™-2002 is the function of (complete empirical formula see the standard IEEE 1584™-2002):

$$I_{a(IEEE)} = f(K, I_{k3}^{''}, U_n, d) \qquad (5)$$

where K is the type of the configuration (open configuration or box configuration (switchgear, panel, cable)). $I_{k3}^{''}$ is the short-circuit current in kA, U_n is the rated voltage in kV and d is the electrode gab in mm. Function (5) calculates arcing fault current $I_{a(IEEE)}$ in kA. Waveforms of arcing fault currents I_a and $I_{a(IEEE)}$ are shown for the electrode gab d=25 mm and the rated voltage U_n=400 V on Fig. 1. Whereas the current limiting factor k_B was calculated for the ratio R/X=1 and the ratio R/X=0,2 in the equation (4). In the calculation of the current limiting factor k_B we assumed 80 % quantile of the arc voltage U_b. Finally the type of the configuration was considered as the box configuration in the function (5).

The standard IEEE 1584™-2002 provides the empirically derived model which is based on actual data and it is valid for the rated voltages U_n between 208 V and 15 kV, short-circuit currents between $I_{k3}^{''}$ 700 A and 106 kA and electrode gabs d between 13 mm and 153 mm. For other cases the standard IEEE

1584™-2002 provides a different equation which is from a theory based model of the arc flash and which is also referred to as the "Lee Model". Next we will focus only on empirically derived model.
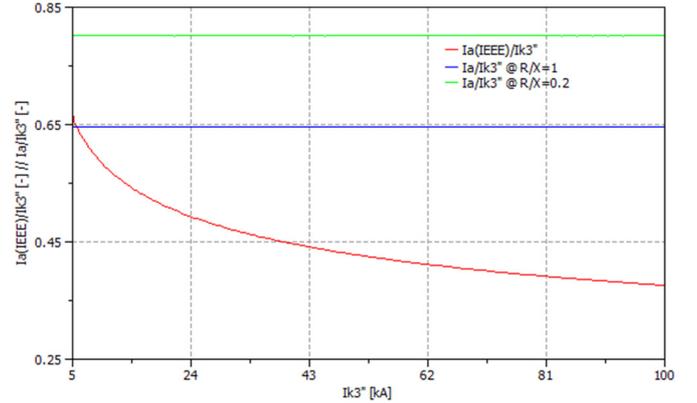

Fig. 1. Arcing Fault Currents

Normalized incident energy $E_{ni(IEEE)}$ is defined as the function:

$$E_{ni(IEEE)} = f(K, K_1, I_{a(IEEE)}, d) \qquad (6)$$

where K_1 is the type of the grounding (ungrounded or grounded system), $I_{a(IEEE)}$ is the arcing fault current in kA and d is the electrode gab in mm. Function (6) calculates the incident energy in J/cm^2 normalized for an arcing duration t_k=0,2 s and the working distance a=610 mm. Incident energy $E_{i(IEEE)}$ can be then calculated from the normalized incident energy $E_{ni(IEEE)}$ using the function:

$$E_{i(IEEE)} = f(C_f, E_{ni(IEEE)}, t_{k(I_{a(IEEE)})}, a, x) \qquad (7)$$

where C_f is the voltage factor, a is the working distance in mm, $t_{k(Ia(IEEE))}$ is the duration of arcing dependent upon the actual settings of tripping curve of the respective protection device and the actual arcing fault current $I_{a(IEEE)}$, x is the distance exponent which is the function of the rated voltage U_n and the equipment type. Arc Flash Boundary is then defined as the distance from the electric arc to the place where incident energy drops to $E_{i(IEEE)}$=5 J/cm^2.

III. ARC FLASH RISK ASSESSMENT

EN 50110-1 ed. 3 (Operation of electrical installations) calls for an Arc Flash Risk Assessment. Should any work in the vicinity of an electrical installation or under live conditions be necessary, a risk assessment must be carried out. As hazards due to electric arcs cannot be completely eliminated for the foreseeable future, the appropriate protective measures should be put in place. Additionally, workers other than electricians (such as operators) may be within reach of electric arc hazards. This should therefore be included in the risk assessment. Based on these facts it was developed a consistent 4-step model for arc flash risk analysis. It always starts with defining the highest acceptable risk and leads through a logical and structured

approach to the interpretation of results proposing different mitigation strategies to control risk see Fig. 2.

Step 1 Identifying hazard and risk consists of two main parts: defining the maximum accepted risk on the one hand, and establishing the operating conditions of the switchgear assembly on the other. As the operating modes (maintenance operation (testing(voltage, current), removing covers, working close to live parts, replacement of fuses, racking breakers etc.) and normal operation (collection of information, meter reading, normal operation through control devices, manual breaker operations etc.)) typically result in separate risk analysis output (risk matrix), this will also be reflected in the proposed protection measures. Additional scenarios including potential failure modes to be evaluated are applicable in case of multiple sources and /or automated load management.
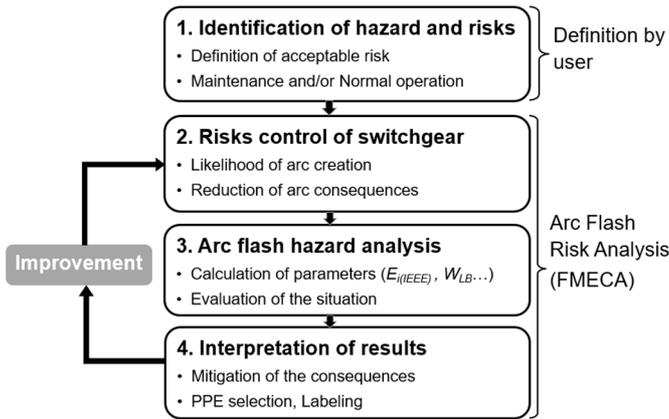

Fig. 2. Arc Flash Risk Assessment

Step 2 Risk control of low voltage switchboards, there are two factors which are needed to be considered the first one is the prevention of arc flashes (protective covers, internal separation, procedures and training etc.) and the second one is the mitigation of the consequences once an arc flash has occurred (settings of protection devices, passive protection etc.).

Step 3 Arc flash hazard analysis, to understand what really happens in the case of an arc flash, it is necessary to calculate a number of parameters such as the arc energy W_{LB} or the incident energy $E_{i(IEEE)}$. Likelihood of an arc event and the calculated incident energy $E_{i(IEEE)}$ defines *risk score* (risk of an arc flash) in the risk matrix, separately for maintenance and normal operation. *Risk score* between 1 – 4 shows low risk, the *risk score* between 5 – 9 shows moderate risk, the *risk score* between 10 – 12 shows high risk and the *risk score* between 15 – 25 shows extreme risk. As a measure of the thermal effect of an electric arc in the risk matrix was choosen the incident energy $E_{i(IEEE)}$ due to the broader range of the selection of PPE see as well below. Likelihood of an arc event at panelboard is the function of protective covers, the internal separation etc. Splitting working activities at a panelboard into two different type of works maintenance and normal operation is necessary since each type of this work has the different type of the conditional probability of an arc event related to this type of the work. Example of the risk matrix is shown on Fig. 3.

Arc likelihood	Thermal effect of Arc Flash (consequences) - $E_{i(IEEE)}$				
	Slight	Minor	Medium	Critical	Catastrophic
J/cm2	<0;5)	<5;16,74)	<16,47; 33,47)	(33,47; 167,36>	(167,36; infinity)
Remote	1	2	3	5	5
Unlikely	2	4	6	8	10
Likely	3	6	9	12	15
Highly Likely	5	8	12	16	20
Almost Certain	5	10	15	20	25

Fig. 3. Risk matrix

Step 4 Interpreting the results, proposing improvements or the definition of an appropriate PPE and printing labels.

IV. IMPLEMENTATION

For the calculation of the arc energy W_{LB} and the incident energy $E_{i(IEEE)}$ we developed a simple tool so called ArcRISK calculator which is convenient especially in cases when there is no information about the anticipated arc energy W_{LB} or the incident energy $E_{i(IEEE)}$ at the low voltage panelboard (workplace). It should be as well noted that results of this tool regarding to arc energy W_{LB} and the incident energy $E_{i(IEEE)}$ are approximate and do not replace the results of the Arc Flash Risk Assessment at this low voltage panelboard (workplace) conducted as the part of the comprehensive Arc Flash Risk Assessment. Screenshot of the ArcRISK calculator can be seen on Fig. 4.

On the left side is the simplified drawing of the low voltage panelboard for settings of parameters of devices for the calculation including type of the supply (from the transformer (as it is shown on Fig. 4) or the upstream low voltage panelboard) and on the right side are two tables with results. The first table "Energy and PPE" contains the results of the calculation and the selection of the appropriate PPE in terms of both test methods. The second table "Risk" contains the risk matrix shown on Fig. 3 where can be set the *risk score* (the risk of an arc flash) by the estimation of the likelihood of an arc event. The estimation of the likelihood of an arc event is done by the user with regard to factors influenced the probability of the arc (see above).

A comparison of both procedures described in the technical report BGI/GUV-I 5188 E and in the standard IEEE 1584™-2002 will be carried out using below shown example. We will consider a low voltage panelboard of the rated voltage U_n=400 V with electrode gab d=25 mm supplied from a utility with the rated voltage U_n=22 kV, the short-circuit power S_k''=500 MVA and the ratio R/X=0,125 through a transformer with the rated power S_n=1000 kVA, the voltage ratio 22/0,4, the impedance of the transformer u_k=5% and the ratio R/X=0,125 exactly as it is shown on Fig. 4. The transformer is protected by the protection relay with this settings I>=144 A, tI>=0,3 s (Definite Time), I>>=640 A, tI>>=0,04 s (Definite Time). As the main low voltage circuit breaker was used a typical molded case circuit breaker with these settings $LTPU$=1445 A, $STPU$=6000 A, STD=0,08 s and $INST$=24453 A. We consider as well two motors supplied from this low voltage panelboard. The first

motor has the rated power S_m=100 kVA, the rated voltage U_n=400 V, the ratio *LRA/FLA*=6 and the ratio *R/X*=0,1 and the second motor has the rated power S_m=60 kVA, the rated voltage U_n=400 V, the ratio *LRA/FLA*=6 and the ratio *R/X*=0,1. In the calculation we neglect impedances of cables and we assume that working distance is *a*=455 mm. Results of the example are show in the table on Fig.5. On Fig. 5 in the table "Energy and PPE" the line side means the side before the main low voltage circuit breaker on the other hand the bus side means the side behind the main low voltage circuit breaker at the panelboard.
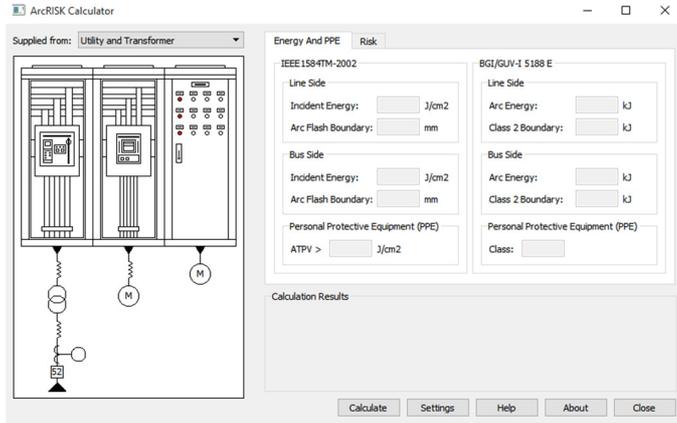

Fig. 4.   Screenshot of the ArcRISK calculator

It can be seen from the results in the example (see results in the table on Fig. 5) that PPE in the Electric fault arc protection class 2 is not adequate for work on this low voltage panelboard. It means that there are not any PPE in accordance with IEC 61482-1-2 (Box test) which could be used in this case. PPE tested for greater incident energy *E* levels must be used. Calculated incident energy $E_{i(IEEE)}$ of the line side (worst case from calculated incident energies for the bus and the line side) belongs to *PPE Level* 3 (recommendation about *PPE Levels* see NFPA 70E-2015, for *PPE Level* 1 is the incident energy between $0 - 5$ J/cm^2, for *PPE Level* 2 is the incident energy between $5 - 16,74$ J/cm^2, for *PPE Level* 3 is the incident energy between $16,74 - 33,47$ J/cm^2, for *PPE Level* 4 is the incident energy between $104,6 - 167,36$ J/cm^2). It means that there are appropriate PPE in accordance with IEC 61482-1-1 (Open Arc test result). Regarding to the standard IEC 61482-1-1, the incident energy (*ATPV*) is determined according to a statistical methodology, by which a 50% probability exists of suffering second-degree skin burns behind the PPE. Example above also shows that the incident energy $E_{i(IEEE)}$ is an appropriate measure of the thermal effect of an electric arc in the risk matrix see above.

V. CONCLUSION

In this paper we shortly described calculation methods defined in the standard IEEE 1584^{TM}-2002 and in the technical report BGI/GUV-I 5188 E and proposed the implementation of their results into the derived 4-step model of the Arc flash risk assessment (FMECA). As an appropriate measure of the thermal effect of an electric arc in the risk matrix in the step 3 of the model of the Arc flash risk assessment we chose the incident energy $E_{i(IEEE)}$. Suitability of this choice was shown in

the example in the section 4. For the calculation of the arc energy W_{LB} and the incident energy $E_{i(IEEE)}$ we developed a simple tool so called ArcRISK calculator. This tool contains as well the risk matrix which is the integral part of the derived 4-step model of the Arc flash risk assessment.

Fig. 5.   Results of the calculation

VI. REFERENCES

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