Simple Improved Equations for Arc Flash Hazard Analysis

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Introduction

The IEEE standard 1584 for performing arc-flash hazard calculations [1] is based on a large number of tests in a steel box, intended to represent typical equipment. The arrangement is illustrated schematically in Fig.1.

Arcing was initiated by fine trigger fuse wires across the electrode tips to produce an arcing fireball, and the energy density at a distance *d* was measured using copper disc calorimeters. Formulae were derived from which the arcing current and incident energy can be estimated.

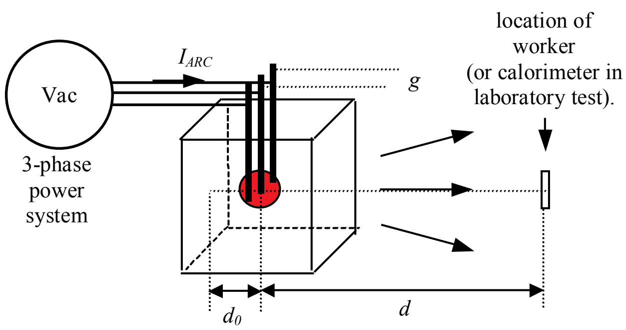

Fig.1 Arc flash in an open box

In [2] a 3-phase time-domain model of this arc flash event was described, which enabled the study of transient effects, the sequential operation of current-limiting fuses in the line, interaction between phases, point-on-wave effects and so on. However the time domain model is complex and is more suitable for research than everyday application.

In this paper a simplified model is described which eliminates anomalies found with the IEEE1584 method, and which gives a better overall correlation with test results.

The IEEE 1584 method

The arc flash calculations proposed in IEEE 1584 require two stages:

(a) calculation of arcing current, so that the operating time (t_{ARC}) of protective devices such as fuses or circuit breakers can be found.

(b) calculation of incident heat energy density at a distance *d* after a time t_{ARC}. This is then used to determine the required level of personal protective equipment (PPE). The variation of incident energy with distance is represented by the use of "distance exponents", which depend on the type of equipment.

The equations given in IEEE 1584 were developed by using a least squares method, to obtain a good statistical fit to the test data, but the grouping of variables was not based on physical phenomena, and can produce anomalous predictions, such as:

- calculated arcing current being greater than the bolted-fault current
- calculated arcing current increasing as the electrode gap increases
- calculated incident energy density being reduced when the electrodes are enclosed in a box
- sudden jumps/discontinuities in the predictions as variables are changed

These anomalies have been discussed in detail in [2] and elsewhere. A simplified version is presented here, which is based on the same concepts as in [2] but which is suitable for general use. It eliminates the anomalies listed above, since it is based on physical models, and gives a better overall correlation with test results than the IEEE 1584 equations.
Although the IEEE 1584 standard has been updated since its original publication, and additional testing work has been carried out recently, at the time of writing there has been no change to the basic method of analysis, which is to use a purely statistical fit to the data.

Basic ideas

(a) Calculation of arcing current

For the calculation of arcing current, the basic idea is that behaviour of the electrical power system is well known and can be modelled accurately. The main unknown is the arc characteristic. If the arc is represented as a resistor and its interaction with the source circuit is calculated, the resulting arcing current *must always be lower* than the bolted-fault current.

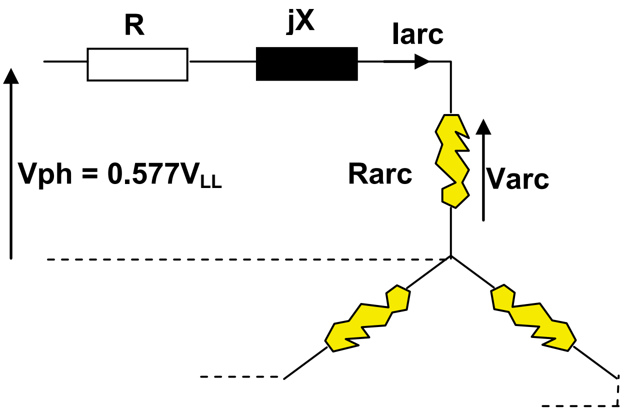

Fig. 2 Single-phase model of a 3-phase arcing fault

These effects can be represented by the equivalent circuit shown in Fig.2, which was originally used by Fisher [3]. The three-phase arcing fault is modelled as a set of three Y-connected arcs. Arc current and voltage are represented as r.m.s. values, and the use of phasor calculations implicitly assumes that their waveshapes are sinusoidal, (which they are not). However, the problem of non-sinusoidal waveshapes can only be solved by the use of something like the time-domain method.

For the simplified version, the effect of harmonics (principally in the voltage wave) is absorbed into the coefficients generated when fitting the models to the test data.

(b) Calculation of incident energy density

For the calculation of incident energy density, the basic idea is that the effect of a box enclosure has a focussing effect. Radiated energy strikes the back and sides of the box and is then reflected out towards the calorimeters. This gives a higher incident energy density than would be obtained in the open. *These comments are only valid for the radiated components of heat flux. If the electrode arrangement were changed so that plasma jets drive the plasma cloud in the direction of the calorimeters, an additional heating term would need to be included.*

Data set used

The data used for this work were taken from the Test Results Database appended to the IEEE 1584 document, augmented by 37 tests done in 2004 [2]. The total number of useable sets of test data was 347. A reduced set of data was also used, formed by replacing the data for replicated series of tests by a single, suitably "averaged" result. The reduced set gave results close to those obtained for the whole set.

Equation for Varc

The key to the whole process is to find a suitable value for the r.m.s. arc voltage. This then enables the arcing current, power, and energy delivered to be calculated, using the circuit of Fig.2. Analysis of the data (details given in Appendix A-1) gave the following equation for the r.m.s. arc voltage.

$$V_{ARC} = 1.757\, I_{ARC}^{\;0.1457}\, g^{0.2476}\, V_{LL}^{\;0.4166} \qquad (1)$$

where I_{ARC} = r.m.s. arc current, A
g = electrode gap, mm
V_{LL} = line-line source voltage, V

The dependence of V_{ARC} on arc current and gap is similar to that reported previously for single and three-phase tests in several laboratories world-wide [2]. The dependence on V_{LL} is less easy to explain, and has been discussed in [2]. However, it enables the equation (1) to be used over the whole range of voltage, from 208 to 13,800V.

Equation (1) applies for open tests. For tests in a box, the formula must be multiplied by 0.821. The lower arc voltage for tests in a box is probably due to the fact that in the IEEE 1584 test arrangement, the arcs are driven downwards and hit the bottom of the box, restricting their length. For tests in the open, the arcs are free to elongate, giving a higher voltage.

As an alternative, the arc resistance can be used in calculations. From (1) it is given by:

$$R_{ARC} = 1.757\, I_{ARC}^{\;-0.8543}\, g^{0.2476}\, V_{LL}^{\;0.4166} \qquad (2)$$

Calculation of arcing current

The power system is characterised by three variables, the source voltage V_{LL}, the bolted-fault current I_{BF} and the ratio X/R. From these the source resistance R and inductive reactance X can be found. The arcing current is then given by (see Fig.2):

$$I_{ARC} = \frac{V_{PH}}{\sqrt{(R_{ARC} + R)^2 + X^2}}$$

(3)

```
    I_ARC^OLD = I_BF
1   calculate R_ARC using (2)
    calculate I_ARC^NEW using (3)
    error = (I_ARC^NEW - I_ARC^OLD) / I_BF
    if (error > 1e-6) then
      I_ARC^OLD = I_ARC^NEW
      go to 1
    endif
    done ...
```

Unfortunately, R_{ARC} is a function of I_{ARC} and so (3) cannot be solved explicitly for I_{ARC}. However (3) can be solved very easily using the iterative method first described by Fisher [3]. Starting with an arcing current equal to the bolted-fault current, R_{ARC} is found from (2), and substituted in (3) to get a new value of I_{ARC}. This is repeated until the iterative process converges. The process is simple to program on a calculator, spreadsheet, or in other software, and it converges quickly and reliably. It can be represented by the pseudo-code fragment shown above.

Fig.3 shows a comparison of the arcing current calculated by this method with the test values. The r^2 value is slightly lower than was obtained using the time-domain model, but higher than the IEEE 1584 model, for which r^2 was 0.969.

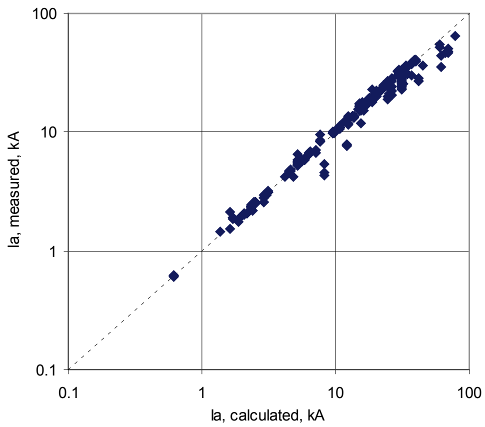

Fig.3 Comparison of calculated arcing current with test values (r^2 = 0.984)

Incident energy density equation (open tests)

After the r.m.s. arcing current has been found, the total arc energy can be calculated from

$$W_{ARC} = 3\, V_{ARC}\, I_{ARC}\, t_{ARC}$$

(4)

where t_{ARC} is the duration of arcing. If the heat transfer to the calorimeters is by radiation only, it should be strongly dependent on the spherical energy density βE_S where β is the fraction of the arc energy which is emitted as radiant heat and

$$E_S = \frac{W_{ARC}}{4\,\pi\, d^2}$$

(5)

When radiant heat is the dominant heat transfer mechanism, tests confirm that the "distance exponent" for open tests is close to 2. However, a distance exponent of 2 will only be exact for a point source of heat or if *d* is very large in comparison with the size of the radiating object. Furthermore, the fraction β will be affected by the electrode gap *g* and other factors.

Correlating the maximum measured energy density values (92 tests) gave the following best-fit to the open test data:

$$E_{MAX} = 114.9\, E_S^{\,1.0655}\, g^{0.2562}\, V_{LL}^{\,-0.5697}$$
(6)

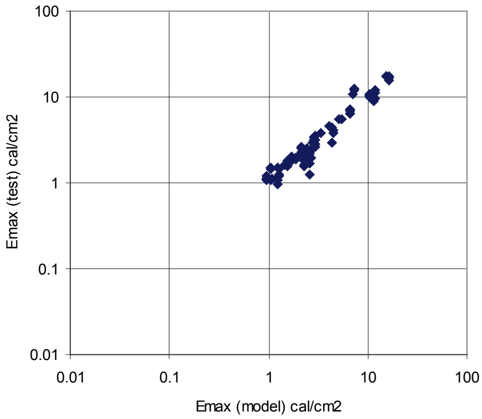

Fig.4 Comparison of calculated incident energy density with test values (open tests only)

Fig.4 shows the correlation between the predictions of equation (6) and the test measurements. For this plot r^2 = 0.947, almost the same as was obtained with the time-domain model [2].

Incident energy density equation (box tests)

The basic assumption is that the same dependencies as found in equation (6) for the open tests can be used, but with the spherical energy density component E_S increased to a value E_1 that accounts for the additional reflected heat radiation. In [2] the single and multiple reflections from the back and sides of the box were computed explicitly, but this is a very complicated process, and for the present work a simplified version was used. It was assumed that

$$E_1 = k \frac{W_{ARC}}{a^2 + d^2}$$
(7)

where *k* and *a* are box parameters. E_{MAX} is then calculated by modifying (6) to

$$E_{MAX} = 114.9\, E_1^{\,1.0655}\, g^{0.2562}\, V_{LL}^{\,-0.5697}$$
(8)

Use of equation (7) is an alternative to the use of distance exponents. The rationale for this is as follows.

For a large radiating object the distance exponent is 2 only at very large distances. Nearer to the source the local exponent falls. It tends towards zero as the object is reached (plane wave). This characteristic is built in to the form of (7).

Equation (7) is exactly the form of the reflection factor from a disk of radius *a* to a point at some distance *d* [4]. We are effectively representing the (arcs+box) as a single heat source with a characteristic dimension *a.* For a point source *a=0* and in this case (7) must degenerate to the spherical formula, so the lowest possible value of *k* is $(1/4\pi) = 0.07957$.

The optimum values of *k* and *a* (i.e. which gave the least-squares best fit to the test data) were determined for each of the three equipment classes specified in IEEE 1584. (These are related to the dimensions of the box). The results are shown in the table below.

	width (mm)	**height (mm)**	**depth (mm)**	**Area of inner surface, (mm^2)**	R_{EFF} **(mm)**	***a*** **(mm)**	***k***
Open	-	-	-	-	-	0	0.07957
Panelboard	305	356	191	361082	339.0	100	0.127
LV switchgear	508	508	508	1290320	640.9	400	0.312
MV switchgear	1143	762	762	3774186	1096	950	0.416

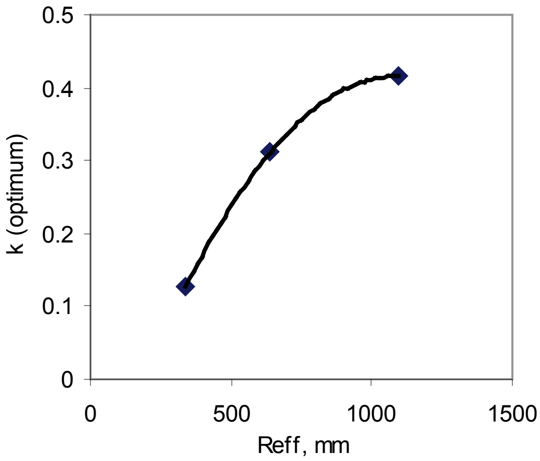

Fig.5 Dependence of *k* on equipment size

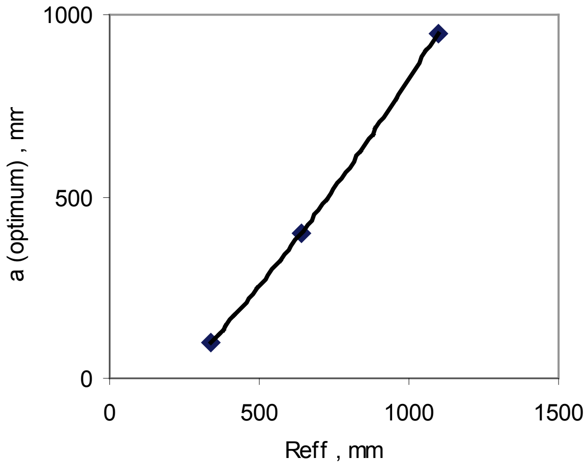

Fig.6 Dependence of *a* on equipment size

R_{EFF} is the radius of a disk which has the same area as the inner surface of the box. It was found that the optimum values of *k* and *a* correlate strongly with the box dimensions. This is illustrated in Figs 5 and 6.

Using Figs. 5 and 6 it is possible to estimate the values of *k* and *a* for box sizes other than those specified in the standard.

Fig.7 shows a comparison of the measured incident energy density with the predictions, for the whole data set (347 tests). Equations (5) and (6) were used for the open tests, while (7) and (8) were used for the box tests, with the appropriate k and a.In this case the r^2 value is significantly higher than is obtained with the IEEE 1584 model, for which r^2 is 0.763.

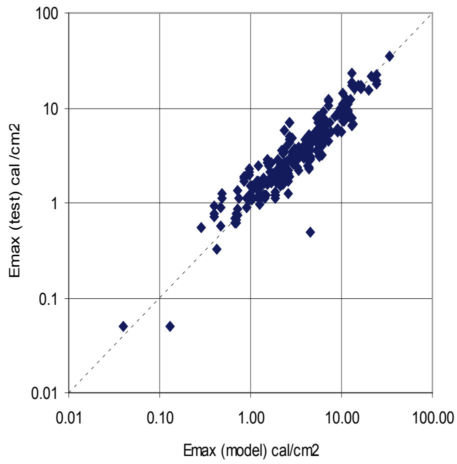

Fig.7 Comparison of calculated incident energy density with test values (all tests, r^2 = 0.860)

Current-limiting fuses

The simplified method given here can only be used for fuses if the bolted fault current is below the threshold of current limitation. For higher fault currents the current-limiting action gives a dramatic reduction in incident energy, as illustrated in Fig.8.

The bend in the characteristic corresponds roughly to the 0.01s point on the fuse's time-current characteristic. For higher fault currents the arc flash energy density is well below the critical value for a 2nd-degree burn (1.2 cal/cm^2).

Conclusion

The proposed simplified method gives results that are based on real physical models, and which overcomes the anomalies built in to the current IEEE 1584 equations. Use of the arc voltage equation (1) ensures that the arcing current is always lower than the bolted-fault current and that it decreases as the electrode gap increases. Use of equation (8) ensures that the incident energy density increases when an arcing fault is enclosed in a box.

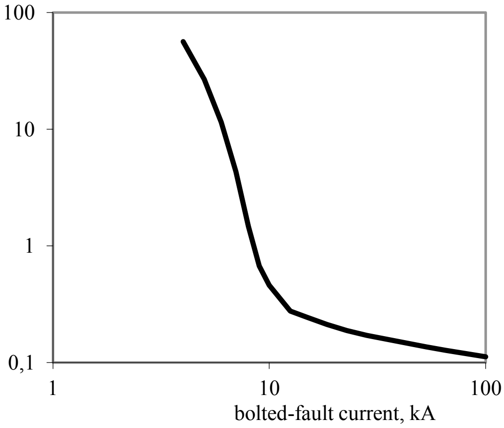

Fig.8 Typical arc-flash characteristic for a 600A current-limiting fuse

The method also gives better overall correlations with test data than the equations in IEEE 1584, especially for the incident energy density values.

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Appendix 1 - Method used for calculating Varc

V_{ARC} in equation (1) is the effective (r.m.s.) phase-neutral arc voltage. Measured values of arc voltages are not available for many of the tests in the data set. Furthermore, when they are available they are line-to-line values. (The phase-neutral value cannot be measured directly as the neutral point is somewhere in the middle of the arc plasma!) In addition, accurate measurement of the arc voltage is difficult because of the erratic nature of the waveform.

For these reasons an *implied* value of r.m.s. arc voltage was used for the development of the arc voltage equation. This is the method used by Fisher [3]. V_{ARC} can be derived from the r.m.s. arc current (which is easy to measure accurately).

If I_{ARC} is known, it is simple to calculate the r.m.s. arc voltage which will produce this value of circuit current, for the circuit of Fig.2. The calculation is as follows.

$$R_{ARC} = \sqrt{(V_{PH} / I_{ARC})^2 - X^2} - R$$

then

$$V_{ARC} = R_{ARC} \, I_{ARC}$$

However, this method gives numerically inaccurate results if the arcing current is very close to the bolted-fault current. Data sets were only used for the calculation if the arcing current was less than 95% of the bolted-fault current. This gave 243 sets, which were used in a multiple regression fit to give equation (1), for which $r^2 = 0.907$.

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