ARC VOLTAGE FOR ARCING FAULTS ON 25(28)-kV CABLES AND SPLICES

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Abstract - Hazards to people and property due to arcing faults on medium-voltage underground cables and splices are related to the arc power dissipated in the environment by the arc. However, if the fault current may be accurately predicted from known circuit parameters, the arc voltage needed to evaluate the arc's power has no analytical expression due to the fact that the arc resistance is non-linear. On the other hand, the arc voltage is also strongly dependent on the inherent physical properties of the faulted equipment, so that in order to establish the arc voltage value and shape developed by different currently used types of equipment, a series of staged tests was performed at IREQ's high-power laboratory and other available data were collected. The results obtained prove that for arc power calculation purposes the arc voltage curve may be considered flat-topped and of constant amplitude specific to the type of faulted equipment.

Keywords: arcing fault, arc voltage, underground distribution.

INTRODUCTION

Arcing faults on medium-voltage (MV) underground cables and splices do not occur frequently but can draw a considerable amount of electrical energy from the system. This energy is dissipated into the environment in various forms and as a result, the safety of the public and utility workers may be jeopardized through one of the following mechanisms.

Melting and evaporation of the electrode material produces droplets of molten metal and vapors which, when violently expelled into the ambient air, can cause local burns and set fire to clothing and other easily combustible materials nearby.

Noise produced by powerful ac arcs can cause irreversible damage to the human ear.

Jets of very-high-temperature vapors and ionized gases can cause serious burns to those struck by the jet.

Temperature and pressure rises in a limited volume of a closed manhole can cause the manhole cover to be violently ejected, thereby allowing the hot gases to escape.

Thermal degradation (pyrolysis) of nearby organic materials generates combustible gases which may react instantly with the ambient air (oxygen), producing flames and smoke and providing an additional heat input in the manhole.

In addition, there are also other arc energy dissipation mechanisms that come into play, namely, radiation and electrode heating, but in the case of faults on MV cables and splices the energy dissipated through these mechanisms is rather slight and the hazards are of minor importance.

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Even if ultimately the arc-induced effects are due to the amount of energy released by an arc, the related damages are in general strongly dependent on the arc's power, or, in other words, on the product of the arc current and the arc voltage. Though the arc current curve may be predicted and expressed analytically with acceptable accuracy from the known circuit parameters, the arc voltage curve has no analytical expression because of the non-linear arc resistance which is dependent on the physical properties of the faulted equipment and results in strongly distorted arc voltage waveshapes (1). Consequently, a knowledge of the arc voltage appears to be one of the most important factors for evaluating the potential arc-caused hazards for different types of equipment. The available data, however, are rather fragmentary and only concern certain types of equipment. In order to supplement the data for other types of equipment, Hydro-Québec's Distribution Directorate performed a series of tests at IREQ's testing facilities. Also, to supplement the available data, the Canadian Electrical Association allowed us to include pertinent data obtained within related R&D projects (1, 2). The results of these investigations for 25(28)-kV equipment are reported in this paper.

TYPE OF EQUIPMENT STUDIED

Taking into account that current practice in 25(28)-kV rated voltage underground distribution systems involves using single-phase, concentric neutral cables with a polymeric insulation, the investigation was focused on the XLPE cables and splices used on such cables. Consequently, the fault arc behavior on the following types of 25(28)-kV equipment was studied:

XLPE single-phase cables, radially faulted by boring a narrow hole in the cable insulation and connecting the live conductor with the grounded concentric neutral using a thin fusing wire.

Type A pre-molded splices with separable housing comprising a relatively short cylinder-shaped plug and socket-like receptacle, faulted by means of a thin fusing wire running along the interface between the plug and socket elements and connecting the live connector with the grounded concentric of the splice bypass as shown in Fig. 1.

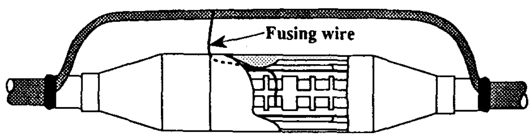

Fig. 1. Position of the interfacial fault on a type A splice.

Type B pre-molded splices with separable housing comprising a relatively long cone-shaped plug and socket-like receptacle An interfacial fault was created in a similar way as for type A splices (see Fig. 2).

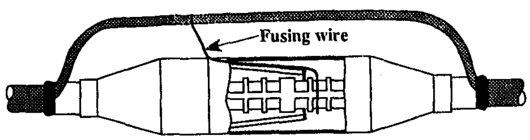

Fig. 2. Position of the interfacial fault on a type B splice

Type C heat-shrinkable splices faulted using an interfacial or radial method as depicted in Fig. 3.

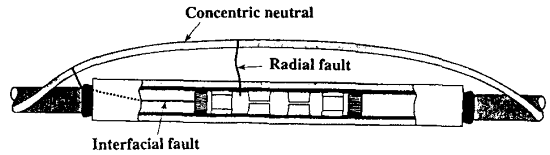

Fig. 3. Position of the interfacial and radial faults on a type C splice.

Type D pre-molded splices with non separable housing and end caps were faulted using an interfacial or radial method similar to the one used for type C splices (see Fig. 4).

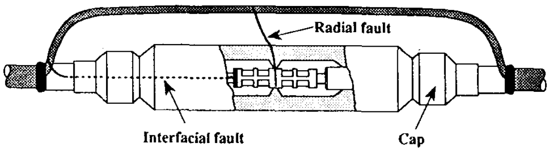

Fig. 4. Position of the interfacial and radial faults on a type D splice.

Type E pre-molded splices with non-separable housing were faulted using an interfacial or radial method similar to the one used for type C splices (see Fig. 5).

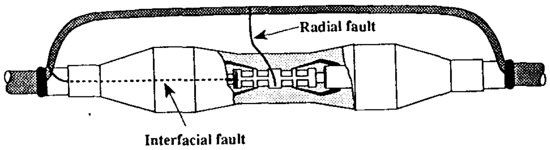

Fig. 5. Position of the interfacial and radial faults on a type E splice.

The method of creating the faults was based on an IREQ study for the Canadian Electrical Association concerning the failure pattern of various types of splices (3). For instance, the study proved that the breakdown on a heat-shrinkable type C splice mostly occurs longitudinally between the connector and the cable's semi-conductor sheath (interfacial fault). The most probable reason for such a failure mechanism is the loss of adhesion between layers due to the thermo-mechanical stress the layers are subjected to under working conditions. Poor workmanship may considerably worsen this situation. Radial breakdown may occur in cases where an aged or bad connection causes considerable local overheating in the center of the splice.

By contrast, the same study proved that breakdown in pre-molded type D and E splices, almost always occurs in a radial direction, in the center of the splice. The reason for this is that the connector is subject to relaxation phenomena after the release of the compression load and to the subsequent thermal effects due to the variable cable electric load. All this can have adverse effects on connection performance, and may cause an increase in its electrical resistance (4). This generates a local hot spot which accelerates contact surface oxidation so that connection resistance increases, etc. As a result the connector often becomes the hottest element inside the splice, touching the splice wall at the center, which causes accelerated ageing of the insulating material at this point. We consider, however, that interfacial breakdown is also possible on this type of splice, such as in the case of a splice that has been poorly installed or because of a hidden manufacturing flaw.

To our knowledge, the failure mechanism for type A and B splices was never studied in depth. We suppose, however, that poor workmanship during installation may be a major cause. For example, during the course of the project reported in ref. 1, we found that a broken vent rod used during installation left in the interface between the plug and socket elements leads to a quick splice failure. On the other hand, local splice body overheating due to the same phenomena as in the case of type D and E splices may always come into play. Nevertheless, whatever the failure mechanism, the separable splice and therefore arc behavior are always quite similar so that the fault initiation method for this type of splices is of minor importance.

In addition, though somewhat beyond the scope of this study on 25-kV equipment, a few samples of three-phase 12-kV PILC cables and field-tapped splices were tested. The samples were radially faulted by boring a narrow hole in the cable or in the middle of the splice body and perpendicular to it. A steel wire 0.5 mm in diameter was used to connect one phase conductor with the grounded cable sheath or lead sleeve of the splice.

TEST CIRCUIT AND PARAMETERS

In general, all tests, except for PILC cables and splices, were performed in a single-phase circuit as shown in Fig 6. For PILC equipment, all three phase conductors were energized.

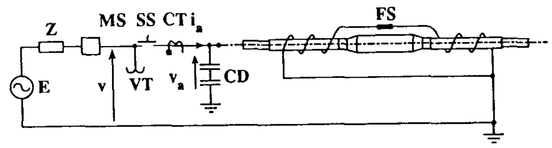

Fig. 6. *Test circuit diagram.*
E - source; Z - circuit impedance ; MS - master switch; SS - synchronous switch; VT - voltage transformer; CT - current transformer; CD - capacitive divider; FS - faulted splice.

The following quantities were recorded for all of the tests:

- applied voltage: v
- arc current: i_a
- arc voltage: v_a
- arc power: $P(t) = v_a i_a$
- arc energy: $W(t) = \int^t v_a i_a \, dt$
- Joule integral: $[I^2t](t) = \int^t i_a^2 \, dt$
- charge (for recent tests): $Q(t) = \int^t |i_a| \, dt$

The tests were generally performed at driving voltages of 7.2 kV and 14.4 kV, which provided good arc current stability and an almost ideal match with the prospective current curve (1, 2), defined as the current that would flow in the circuit if the arc were replaced by a conductor of negligible impedance. For instance, if we assume that the fundamental harmonic of the arc voltage V_{a1} is almost in quadrature with the voltage drop on the circuit impedance (very low circuit PF), the ratio of the symmetrical rms current in the arc (arcing current), to the rms value of the symmetrical prospective current is given by the approximate expression $[1 - (V_{a1}/V)^2]^{0.5}$. For example, for $V_{a1} = 2$ kV and V = 7.2 kV, we obtain $[1 - (2/7.2)^2]^{0.5} = 0.98$, that is, the arcing current attenuation due to the arc resistance is about 2%. For driving voltages of 14.4 kV, this attenuation will be less than 0.6%. Bearing this in mind, in the considerations that follow, the arcing current curve is considered to almost exactly match the prospective current shape and value.

With respect to the fault currents tested, tests were performed for prospective currents ranging from about 4 to 16 kA. This range was expected to be the most representative for fault currents that can be encountered in the actual underground distribution systems rated 25(28)-kV (2).

A large portion of the tests was performed at full prospective current asymmetry while the fault duration varied considerably, i.e. from a fraction of a half-cycle (for faults cleared by a fuse) to several cycles.

As for the circuit PF, considering that many utilities use current-limiting reactors in their distribution systems, its value may be very low. All tests, therefore, were performed at the natural testing circuit PF, but not higher than 0.06 even for the highest prospective currents.

GENERAL OBSERVATIONS ON ARC VOLTAGE FOR DIFFERENT TYPES OF EQUIPMENT

Fig. 7. shows the sample recordings of the arc current and voltage for XLPE cables, type A and type B splices respectively.

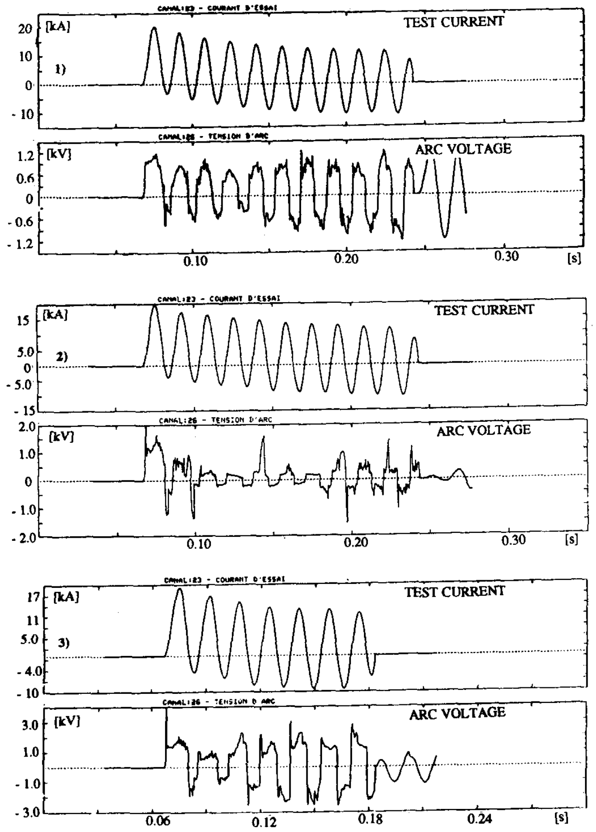

Fig. 7. Sample recordings of the arc current and voltage during faults on: 1) XLPE cable, 2) type A splice and 3) type B splice.

It may be seen that for XLPE cables and type B splices the arc voltage waveshape may be considered to be virtually flat-topped, while for type A splices this is only a very rough approximation. This difference in the arc voltage waveshape is due to the different equipment design which entails different environmental arc-burning conditions and can be explained as follows:

- In the case of XLPE cables, the initial arc length is approximately equal to cable insulation thickness, i.e. about 10 mm for 25(28)-kV cables, and the arc burns in a narrow discharge channel. For powerful arcs, however, the strands of the concentric neutral adjacent to the discharge channel break almost immediately because of arc-induced erosion, and the arc jumps from one strand to another and elongates erratically which results in ripples on the arc voltage wave. Nevertheless, a section of the arc still remains inside the channel where it undergoes intense cooling by blowing insulation decomposition gases and develops a strong arc voltage drop. As a result, the arc voltage wave is more or less rectangular and its average value, defined as the half-cycle arithmetic mean value, is quite high, about 800 V. This is much higher than could be expected for a free-burning arc in air that is a few centimetres long.

  In the case of faults on type A splices, the splice opens very quickly under internal pressure, and the arc becomes virtually free-burning in air, while influenced however by the decomposition gases from nearby organic materials. The arc is subjected to the turbulent blowing of these gases and becomes very unstable, changing its length and cooling conditions. This results in a very unstable arc voltage as regards average value and waveshape. Nevertheless, over a longer arcing period, some regularity may be observed, in particular with respect to the mean value of the average arc voltage, approximately equal to about 600 V.

  In the case of faults on type B splices, the mean average arc voltage is the highest, about 1400 V, and its waveshape is more regular than for type A splices. This is because of the particular design of this splice where the cone-shaped plug element is never totally removed from the socket-like element, so that a kind of nozzle is formed between two parts. The arc is moderately cooled by the blowing decomposition gases but due to its length of about 30 cm develops a fairly high voltage drop. In addition, because of this nozzle effect, the arc voltage is well stabilized so that it has an almost flat-topped waveshape and a constant mean amplitude.

The stabilizing effect of a narrow discharge channel was strongly confirmed by our tests on other types of splices. Fig. 8, for example, shows the sample recordings of the arc current and voltage for type C splices tested at 5 and 10 kA prospective currents respectively.

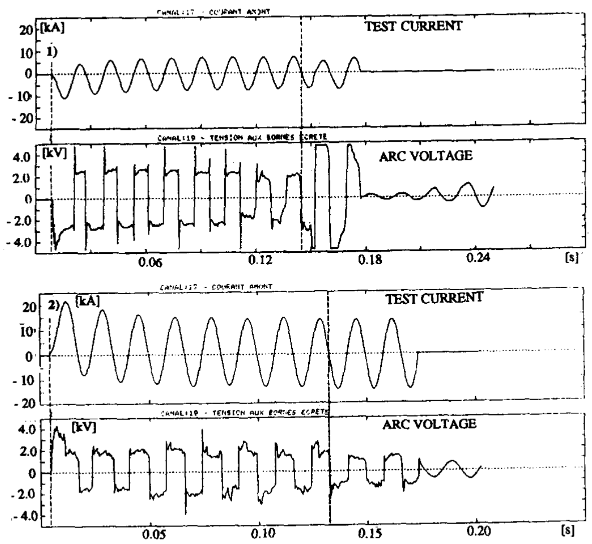

Fig. 8. Arc current and voltage during interfacial fault on type C splices at prospective current: 1) 5 kA and 2) 10 kA.

Here, during a test at a relatively low asymmetrical current of 5 kA rms where the amplitude of the first major loop was of about 11 kA peak, the 20-cm long arc burned in a narrow channel between the splice body and the cable where it underwent very intense cooling and thus developed high arc voltage. During this time the splice did not incur any visible damage so that the cooling conditions were similar for all subsequent loops; consequently, the arc voltage wave was very regular, flat-topped and practically of constant amplitude of about 2700 V. (This was followed by an accidental flashover.) The external section of the arc was also several centimetres long, but a voltage drop along this section was much lower than in the confined interfacial section. It must be added that due to its design, the splice once installed cannot be displaced without being destroyed.

By contrast, while performing a similar test at an asymmetrical current of about 10 kA rms with an initial major loop amplitude of about 22 kA peak, the pressure rise inside the discharge channel was so high that the splice was locally torn within a few milliseconds after the arc inception instant. The arc was then switched from the interfacial channel to the new one. Here, at the very beginning, the arc voltage is very high, over 3000 V, which is evident of very intense arc cooling in a narrow long interfacial channel. The instant of splice tear is marked by a sudden decrease in arc voltage to about 2000 V. The voltage remains at this high level during subsequent loops because the splice tear was quite narrow and only somewhat shorter than the initial channel.

By observing the results and the location of the tear on this type of splice, we noted that for prospective currents higher than 8 kA rms the splice body always tore within a few milliseconds and the subsequent arc voltage was dependent on the position of the tear. When the tear occurred more towards the center of the splice, the fault became virtually radial and the arc voltage only attained about 1000 V or less. By contrast, when the tear occurred more towards one of the ends of the splice, the arc path within the splice body was much longer and the arc voltage attained about 1500 V or more. The location of the tear cannot be predicted because it depends on the splice execution under field conditions and on manufacturing differences.

As for radial faults on type C splices, we observed that the arc voltage remained flat-topped, but because of the much shorter discharge channel of about 15 mm, the average arc voltage was only about 740 V.

The similar nozzle effects were also observed in the case of interfacial faults on type D and E splices as may be deduced from the recordings in Fig. 9.

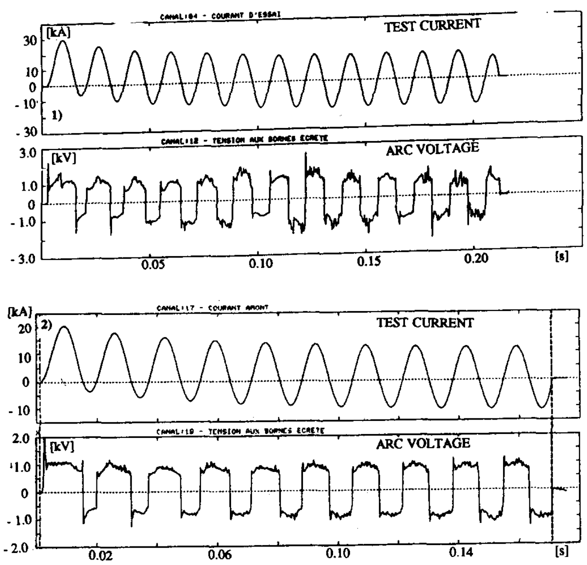

Fig. 9. Arc current and voltage during interfacial fault on: 1) type D splice and 2) type E splice.

In these two cases the interfacial fault also started in a narrow channel about 10 cm long, between the splice body and the cable, but due to a violent ejection of hot gases (jets) through the discharge channel, the quasi-rigid splice housing was very quickly propelled in a direction opposite to the fault direction until it was stopped by the strands of the concentric neutral. The lengths of the interfacial discharge channel then shortened to about one centimetre, and developed lower arc voltage. Nevertheless, along this section the arc is always strongly cooled and develops the regular flat-topped arc voltage of about 900 V in amplitude.

With a radial fault being most likely on type D and E splices, the behavior of the splices, and consequently that of the arc, may vary significantly depending on the situation:

- Under the effect of internal pressure the splice housing moves to the opposite side of the arc and fault becomes quite rapidly interfacial;

- The splice does not move and the fault remains radial in nature developing an arc voltage similar to that for interfacial arcs:

- The splice does not move but under the effect of internal pressure the jets escape through the interstices The fault remains radial in nature but 1 or 2 additional interfacial arcs appear, thus lowering the arc voltage to about 500 V.

The arc behavior for 12-kV PILC cables and splices is quite regular due to the fact that immediately after arc inception the lead sheath of the cable or sleeve of the splice in proximity to the initial discharge channel is wide open, and insulating materials, paper or insulating splice compound are expelled. Subsequently, the relatively short arc burns in a large cone-shaped hole where it is cooled by decomposition gases of the adjacent insulating materials. However, due to the large hole, the nozzle effect is rather weak so that cooling is not so effective, which results in a low arc voltage of about 400 V only. Figure 10 shows an example of the recording of the 8-kA fault on 12-kV PILC cable.

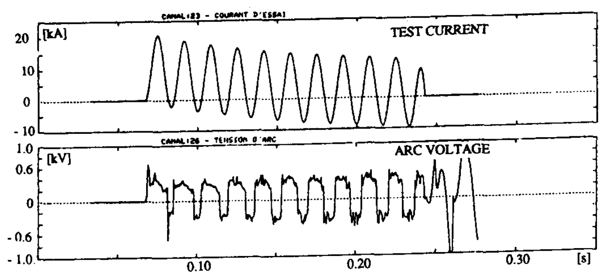

Fig. 10. Sample recordings of the arc current and voltage during fault on PILC cable.

By analyzing the voltage waveshapes, we realized that, except for type A splices, the arc voltage was almost independent of the instantaneous arc current so that its absolute average value is of the same order for both major and minor arcing current loops. Consequently, the arc voltage for all these types of equipment may be considered to be flat-topped and of a constant amplitude V_a specific to the type of faulted equipment and, in the case of type C splices, also to the prospective current interval. This arc voltage characteristic for type A splices is much more erratic, but for the sake of simplicity we will assume that for these splices the arc voltage is also flat-topped and of constant amplitude.

EVALUATION OF TEST RESULTS

Assuming that the arc voltage has a constant amplitude V_a at any instantaneous current value, the arc energy released over a given time interval $\Delta t = t_2 - t_1$, can be calculated using the following formula:

$$W_{\Delta t} = V_a \int_{t1}^{t2} | i_a | \, dt \qquad [1]$$

Notice, however, that in this equation the integral of the absolute arcing current represents the charge through the arc over the time interval Δt, so that the average arc voltage is arrived at using the formula:

$$V_a = W_{\Delta t} / Q_{\Delta t} \quad [2]$$

The values of arc parameters needed for calculations were obtained from the recordings shown in Fig. 11.

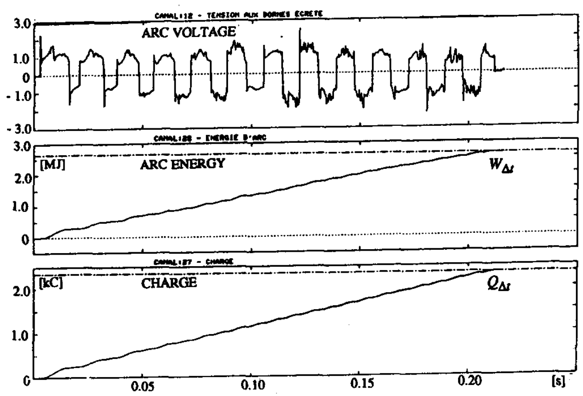

Fig. 11. Sample arc parameter recordings for average arc voltage evaluation.

Here, the average arc voltage was evaluated over the whole relatively long arcing period so that some phenomena linked to the method of arc initiation could be neglected. This evaluation procedure also turned out to be applicable to any time interval within the arcing period, which proved to be very useful for faults of very short fault durations. For instance, in the case of tests where the fault current was cleared by a current-limiting fuse, the time delay between circuit making and arc inception is not negligible. In order to correctly evaluate the charge through the arc, the charge during melting time of the fusing wire used for arc initiation must be subtracted from the total charge through the fault. Sample recordings of a fuse-cleared fault at 8 kA prospective current on a type E splice shown in Fig. 12 demonstrate the procedure used.

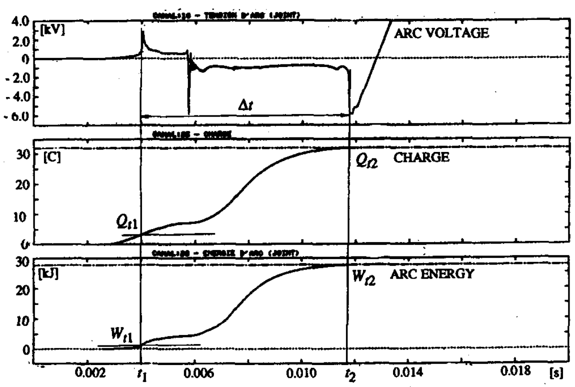

Fig. 12. Evaluation of the arc voltage for faults of very short duration.

In some former tests where the charge through the arc was not recorded, the average arc voltage was calculated on the basis of the arc energy and Joule integral recordings. In fact, from the I^2t curve the virtual rms arcing current over a given arcing period Δt is arrived at by formula:

$$I_{a,\Delta t} = \sqrt{[I^2t]_{\Delta t} / \Delta t} \quad [3]$$

Bearing in mind that the average half-cycle value of this current is $(2\sqrt{2}/\pi)I_{a,\Delta t} = 0.9I_{a,\Delta t}$, the arc energy is arrived at by formula:

$$W_{\Delta t} = 0.9 I_{a,\Delta t} V_a \Delta t \quad [4]$$

Taking into account Eq. 3, the average arc voltage can be calculated from formula:

$$V_a = 1.11 W_{\Delta t} / \sqrt{\Delta t [I^2t]_{\Delta t}} \quad [5]$$

Care should be taken, however, that this formula for general fault cases at any current offset is applicable only for faults lasting at least several cycles. For short faults the error resulting from possible current asymmetry may be considerable.

In order to establish the relationship between the arc voltage and arcing current on the basis of the data collected, a linear result approximation was assumed and the least-squares-regression lines were calculated. Table 1 summarizes the calculation results while Figs. 13 to 16 show scatter diagrams and plots of estimated regression lines for all types of equipment tested. It should be noted that in Table 1, in addition to the equation of the estimate $V_{a,est} = f(I_a)$, where I_a is the arcing current in kiloamperes, the following parameters are provided:

- number of observations:	N
- coefficient of correlation:	R
- modified standard error of estimate (of V_a on I_a):	$S_{Va,Ia}$
- mean value of arc voltage:	$<V_a>$
- modified standard deviation of arc voltage:	S_{Va}

As seen in Table 1, the correlation coefficients for the regression lines are admittedly not very good. This must be partially due to the generally random behavior of fault arcs, but also very much to the fact that the regression line slopes are very low. It may be proven that in such cases even a slight scatter leads to the very random correlation coefficient value; consequently, for low-slope fault regression lines the correlation coefficient is meaningless. Nevertheless, the tendency seems to be clear, namely that within testing current intervals from 4 to 16 kA the average arc voltage for a given type of equipment, except for type C splices, is almost independent of the current value. The comparable values of the modified standard deviation and modified standard error of estimate, except perhaps for PILC splices, confirm this conclusion

The rule on constant arc voltage also applies to interfacial faults on type C splices but there are two distinctive current intervals as follows:

- For prospective currents up to and including 8 kA, an interfacial fault may persist during several cycles, generating a high arc voltage of about 2900 V.

- For prospective currents higher than 8 kA, the splice is torn within a few milliseconds which results in a much lower arc voltage of about 1500 V.

It must be added that the limits between these two ranges are not very clear. In fact, we observed the splice explosion occurring at prospective currents much lower than 8 kA, but we also have evidence to the fact that in some cases the splice supported several cycles of 7 kA arcing current without being torn. Consequently, for the sake of safety we prefer to assume that for faults up to 8 kA the splice may develop a very high arc voltage. We would also like to stress the fact that whatever the prospective current value, the arc voltage within the first major loop of the fault current, i.e., before the splice tore, must be assumed to be very high, namely about 3000 V. This fact must be taken into consideration when evaluating arc-induced hazards such as noise due to the derivative of the instantaneous arc power (5), and when evaluating the effectiveness of current-limiting protective devices.

Table 1. Arc voltage evaluation results

Faulted equipment	Parameter
Type A splices - interfacial fault	$V_{a,est} = 0.608 + 0.003 I_a$ kV $N = 43$ $R = -0.055$ $S_{Va,Ia} = 0.152$ kV $\langle V_a \rangle = 0.577$ kV $S_{Va} = 0.153$ kV
Type B splices - interfacial fault	$V_{a,est} = 0.942 + 0.008 I_a$ kV $N = 17$ $R = 0.148$ $S_{Va,Ia} = 0.178$ kV $\langle V_a \rangle = 1.01$ kV $S_{Va} = 0.174$ kV
Type C splices - interfacial fault for prospective current $I_p \le 8$ kA [1]	$V_{a,est} = 2.60 + 0.036 I_a$ kV $N = 6$ $R = 0.209$ $S_{Va,Ia} = 0.236$ kV $\langle V_a \rangle = 2.85$ kV $S_{Va} = 0.216$ kV
Type C splices - interfacial fault for prospective current $I_p > 8$ kA	$V_{a,est} = 1.59 + 0.007 I_a$ kV $N = 34$ $R = -0.052$ $S_{Va,Ia} = 0.338$ kV $\langle V_a \rangle = 1.53$ kV $S_{Va} = 0.333$ kV
Type C splices - radial fault [1]	$V_{a,est} = 0.623 + 0.004 I_a$ kV $N = 13$ $R = 0.340$ $S_{Va,Ia} = 0.133$ kV $\langle V_a \rangle = 0.807$ kV $S_{Va} = 0.135$ kV
Type D & E splices - radial or interfacial fault	$V_{a,est} = 0.963 + 0.004 I_a$ kV $N = 29$ $R = 0.072$ $S_{Va,Ia} = 0.177$ kV $\langle V_a \rangle = 1.00$ kV $S_{Va} = 0.175$ kV
XLPE cables	$V_{a,est} = 0.450 + 0.027 I_a$ kV $N = 51$ $R = 0.548$ $S_{Va,Ia} = 0.130$ kV $\langle V_a \rangle = 0.703$ kV $S_{Va} = 0.154$ kV
12-kV PILC cables	$V_{a,est} = 0.348 - 0.002 I_a$ kV $N = 5$ $R = -0.562$ $S_{Va,Ia} = 0.017$ kV $\langle V_a \rangle = 0.328$ kV $S_{Va} = 0.017$ kV
12-kV PILC splices	$V_{a,est} = 0.127 + 0.041 I_a$ kV $N = 6$ $R = 0.850$ $S_{Va,Ia} = 0.103$ kV $\langle V_a \rangle = 0.491$ kV $S_{Va} = 0.176$ kV

1) Roughly approximate values.

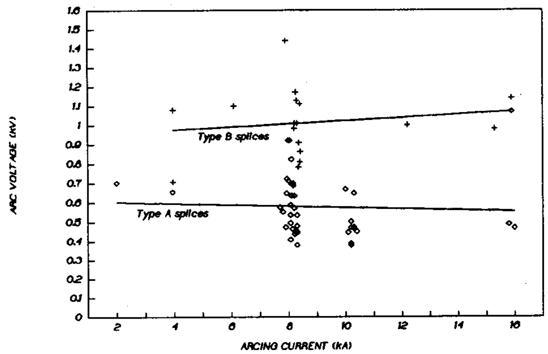

Fig. 13. Arc voltage for faults on type A and B splices.

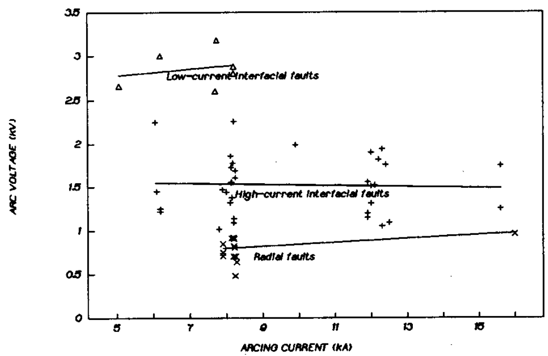

Fig. 14. Arc voltage for faults on type C splices.

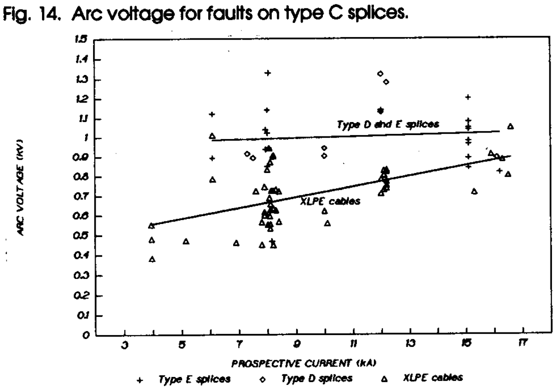

Fig. 15. Arc voltage for faults on XLPE cables and type D and E splices.

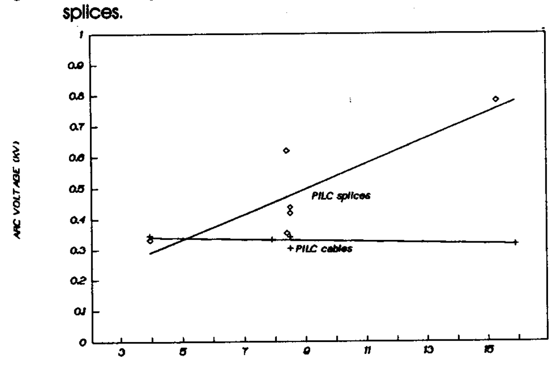

Fig. 16. Arc voltage for faults on 12-kV PILC cables and splices.

CONCLUSIONS

The main conclusions of this paper are summarized below.

1) The arc voltage waveshape can be considered flat-topped and, except for type C splices, independent of the arcing current. Its value, however, is strongly dependent on the type of faulted equipment and often on the kind of fault, interfacial or radial. The arc voltage is generally higher for interfacial faults than for radial ones. This is due to the longer discharge channel in the case of interfacial faults where the arc undergoes intense cooling as a result of insulation decomposition gases, thus developing a high arc voltage.

2) For XLPE cables and type A, B, D and E premolded splices, the arc voltages are specific for a given type of equipment and vary from about 600 to 1000 volts as reported in Table1 .

3) For heat-shrinkable type C splices, the arc voltage varies from about 2900 V for arcing currents from 4 to 8 kA, to about 1500 V for arcing currents over 8 kA up to 16 kA (see Table 1). This arc behavior is due to the fact that for higher fault currents the splice tears very quickly and the fault becomes virtually radial.

4) For 12-kV PILC cables and splices, the arc voltage is quite low due to the fact that immediately after arc inception the lead sheath of the cable or splice is widely open, and the short arc burns in large hole where the arc cooling is rather weak. This result in a low arc voltage of about 400 V.

5) Due to the use of current-limiting reactors, a very low circuit PF has no apparent influence on the arc voltage value and shape. However, the influence of this parameter on the arc energy must be taken into consideration because of a possible high peak value and slow attenuation of the aperiodic component of the fault current.

6) On the basis of the arc voltage values established in this paper, it is possible to calculate the arc energy for fault currents and durations specific for underground distribution systems for any type of equipment tested. Other studies should allow to establish how this energy jeopardizes worker and public safety, which should ultimately allow appropriate mitigative measures to be chosen and developed.

7) The arc voltage values established in this paper can be used to evaluate the arc power and energy for circuits protected by current-limiting devices. In the case of type C splices, however, the arc voltage during the entire fault clearing time must be considered to be equal to that of the interfacial fault before the splice tore, namely about 3000 V.

ACKNOWLEDGMENTS

he authors wish to thank J.-G. Couture of Hydro-Québec's Distribution Directorate for granting us permission to publish this paper.

The Canadian Electrical Association Distribution R&D Committee must be thanked for having allowed us to include data from certain R&D projects (see references).

A word for thanks goes to C. Biondic for careful revision of the text.

Biography

Bohdan Koch was born on August 11, 1932 in Poland. He obtained his master's and doctoral degrees at the Technical University, Warsaw, Poland in 1956 and 1976 respectively. From 1956 to 1981 he worked at the Electrotechnical Institute in Warsaw as research scientist in the field of electrical distribution equipment and was responsible for many research projects in high- and low-voltage distribution. For five years (1970-1975) he was manager of the high-power laboratory. He was a member of the Polish Standardization Committee and Polish delegate to several IEC technical subcommittees.

In 1980 he worked for a time as visiting scientist at IREQ and in 1981 was a consultant for the United Nations Development Program in Brazil. Since 1983 he has been a full-time member of the scientific staff at IREQ where he has specialized in studies of arcing fault phenomena and high-power testing. He is a member of the Ordre des Ingénieurs du Québec and of the R&D Distribution Committee of the Canadian Electrical Association.

Patrick Christophe was born on December 10, 1952 in France. He obtained a B.Sc. in Physics and a master's degree in Electrical Engineering from Laval University in 1975 and 1980. He is a member of the Ordre des Ingénieurs du Québec.

In 1978 he joined Hydro-Québec, where he worked in underground distribution projects in apparatus and standardization. In 1989 he was manager for Apparatus distribution at the head office. He is currently associated with a task force in charge of redesigning the underground distribution network in order to increase worker safety and the quality of customer service.

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Discussion

Ronald F. Frank (Pirelli Cables Inc, Saint-Jean-sur-Richelieu, Quebec): The authors should be commended for their excellent paper, which gives valuable information on the physical meaning of arcing fault on medium-voltage underground cables.

The relatively low arc voltages of XLPE and PILC cables compared to the splices is interesting. Previous tests that have been made simulating dig-in faults on energized cables indicated that the contact voltage is directly related to the gap between the tool and the concentric neutral wire when contact with the cable conductor was established. The contact voltage was found to be high with a single neutral wire, and this voltage decreased as the number of neutral wires was increased. It was also noted in these tests that when the tool contacted the insulated conductor before contacting a neutral wire or when poor contact was made with the neutral wires a higher voltage spike appeared at the inception of the arc and to a lesser degree at each maximum of the voltage cycle thereafter.

The effectiveness of the semiconducting shield of the splices tested is demonstrated, as it appeared to do a surprisingly good job of establishing an arc; however, it alone is not a sufficiently good conductor to limit the arc voltage to a low value. A metallic shield of closely wrapped copper wire would appear to have some advantages.

Manuscript received July 9, 1992.

T. Lipski (Technical University of Gdańsk, Gdańsk, Poland): The main value of the paper consists in:

—statement that the arc voltage wave-shape of arcing fault on 25(28)-kV cables splices can be considered flat-topped and independent of the arcing current,

—evaluation of the arc voltage magnitude for different types of the splices.

More general remark to the paper is on the kind of fault under consideration. Beside arcing faults studied in the paper there are also well known even more severe arcing fault inside of the splices due to loss of a proper contact between cable ends connected in the splices. The process usually starts as a result of that contact aging, which in turn elevates the temperature rise, hence the aging does accelerate, a.s.o. Usually arise an avalanche heating up of the contact up to the eventual loss of metallic contact, then an arc ignition resulting in a secondary effect which is the connecting of the live conductor with the grounded concentric neutral of the splice through the burned out holes in the splice insulation. During such a fault much greater energy can be liberated due to non-operation of the overcurrent protection, while the current is of order of normal load or of permissible overload. A damage to the surrounding in this case can be more disastrous than in the case under study in the paper. That's why it seems advicable to study suggested faults too.

Test circuit diagram (Fig. 6) shows a special connection of the concentric neutral in form of two-sided "coiles" wound around the cable. Had the connection any influence on the arcing behaviour?

Next question is on a strange behaviour of the post-arc voltage across the neutral and the live conductor, visible clear in Figs. 7, 8 and 10. What is the reason of that?

In the Table 1, it seems, there are 2 errors as concerns the slope of arc voltage versus arc current in comparison with the Figs 13 and 14. Namely, the second members of $V_{a,est}$ for types A splices and C splices-interfacial fault should be negative instead of positive.

The final remark is on validity of the results obtained by authors. It seems, for the fault duration longer than studied the flat-topped are voltage can be eventually no more valid, due to expected diminishing of the arc cooling by blowing insulation decomposition gases. The reason is such an enlargement of the hole in the burned out insulation that the arc becomes no more intensive cooled by gases.

Manuscript received July 27, 1992.

V.L. BUCHHOLZ and H.E. ORTON, Powertech Labs Inc., Surrey, B.C., Canada:
The authors are to be congratulated on a very interesting and well presented paper. We have the following points which require elaboration.

1) Conclusion 5 states that in your test circuit the use of current limiting reactors and the subsequent low PF may cause a high peak value of current and a slow attenuation of the aperiodic component of the current. Could you comment on the effects of current limiting reactors used on in-service feeders?

2) In our work [1] we initiated many arcs in oil by using a fuse wire across a gap. Some preliminary investigation was performed by using an impulse generator to initiate the arc. We found no significant difference in arc energy or voltage between arcs initiated with a fuse wire or an impulse. Were all the arcs in your tests initiated with a fuse wire? Have you ever tried initiating power arcs in a cable splice using a high voltage impulse? Do you believe the method of arc initiation in a solid dielectric in a splice has an effect on arc voltage?

3) Our work [2] concluded that XLPE cable operation at elevated temperatures will result in an increasingly stiff or embrittled insulation subject to cracking. We might expect that in old cable splices, especially if they have experienced some high temperatures, although a fault may begin interfacially it may quickly become a radial arc. Were any of your tests performed on aged splices? Could you comment on what effect you would expect splice aging to have on arcing voltage?

4) We have found that fault damage is very dependent upon the materials present during the fault process or by the failure mechanism itself. Would you comment on the effect of copper versus aluminum conductors and PILC versus XLPE insulation?

5) In higher fault current locations and where reclosing is used, the ground wires or "suit case handles" have been known to be blown away from the splice resulting in larger arcing energies as the ground plain is now more remote. Have you experienced this and how does this change the arc voltage and energy?

Reference

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Manuscript received August 10, 1992.

J. P. Bhangu (SaskPower, Regina, Saskatchewan, Canada): The authors conducted tests at 4 to 16 1 > A of fault current and at very low power factors.

In the Canadian Prairies, the 25 kV (line-to-line voltage) 3-wire ground return system is solidly grounded resulting in much higher power factors than those considered by the authors. Line-to-ground faults levels are typically 2000 A at Distribution Substations. At some distance from these substations, the fault currents are extremely low —less than 100 A. In the present overhead system, it is not uncommon to employ 10 A overcurrent reclosers to detect fault levels of 30 A. 25 kV cables and splices are being direct buried in Saskatchewan and in few instances, fault currents could be very low.

Could the authors please comments on the Waveshape of arc voltage expected and the very low magnitude of power dissipated in cable and splice arcing faults.

Manuscript received August 20, 1992.

J. F. Smith (Commonwealth Edison Company, Maywood, IL): The authors have prepared a concise and logical explanation of the mechanism of cable failure and the arc energy produced. This paper is significant because of the intensified focus on worker and public safety relative to manhole and vault explosions.

There has been some discussion that many primary voltage cable failure explosions are the result of the pyrolysis of the failed insulating materials. Our observation of some very eventful cable failures revealed only a very small quantity of insulating material was consumed. Thus there was a disproportionately high release of energy compared to the amount of insulation consumed. This gives credence to the author's contention that it is the arc energy that produces the large amount of energy at the cable fault. And as the authors clearly state, this is the product of the arc current and voltage. We were pleased to see that the authors included PILC cable in there tests.

Manuscript received August 21, 1992.

B. KOCH and P. CHRISTOPHE: The authors thank the discussers for their valuable input and comments.

With respect to the five questions asked by V. Buchholz and H. Orton, we offer the following explanations:

1) According to the survey conducted in the course of the project, some Canadian utilities use current-limiting reactors in their 25(28)-kV feeders, which results in very low circuit PF for faults downstream. Hydro-Québec and North York Hydro, for example, quote circuit PF values of about 0.03 or even lower (Ref. 2). For fully asymmetrical faults at very low PF, an increase of about 10 to 20% in the arc voltage for the first major loop may sometimes be observed. On the other hand, the arc voltage for the first minor loop is somewhat lower than the average value, although the differences vanish with aperiodic-component attenuation so that for arcs lasting several loops the total difference in average arc voltage due to the low PF value and fault asymmetry is negligible. In contrast, in the case of short-duration asymmetrical faults at given prospective current, the influence of the low PF on the peak arc power may be significantly higher because it combines the effects of a higher arc voltage and a high peak-current.

2) We did not use a high-voltage impulse for arc initiation. Nevertheless, we tried different methods of initiating the arc: a cord moisturized with salt water, a deposit of soap film over the cable insulation in the interface between the cable insulation and splice housing, direct application of the driving voltage to previously slightly damaged cable insulation, etc. In all cases we found no significant difference in arc voltage, except perhaps at very beginning because the arc generally struck near the maximum of the driving-voltage wave, preventing us from obtaining an asymmetrical fault. All other faults were initiated using a thin steel or copper conductor. We therefore believe that, for arcs lasting several loops, the arc-initiation method has no effect on the average arc voltage value, provided that the hole, if any, pierced in solid insulation is very small in diameter.

3) In the case of splices subjected to thermal aging, there seems to be more probability of radial faults because of the general deterioration of the splice housing. However, we do not believe that an initially interfacial fault on a premoulded splice can suddenly become radial. The jet effect causes the splice housing to move to the opposite side of the fault, which results in a slight drop in pressure inside the splice, reducing the probability of explosion, except perhaps in the case of splices with excessive loss of mechanical strength due to thermal aging. As for the effect of splice aging on the arc voltage, we suppose there is no significant difference, apart from a possible decrease in arc voltage due to material changes.

4) Arc-induced damage is beyond the scope of this paper. Nevertheless, we observed that copper and aluminum have no significant influence on the arc voltage value and shape for the equipment tested. All PILC cables and splices tested had copper conductors while XLPE cables, except for a few samples, consisted of aluminum-conductor cables with a bare tinned-copper concentric neutral. For arcs on aluminum-conductor cables, we observed much greater conductor erosion than for copper-conductor cables. Aluminum evaporates at a much higher volume erosion rate than polyethylene, with the result that the arc is forced to follow the retreating conductor material within the cable insulation under thermal-degradation conditions. This produces a stronger cooling effect on the arc so that a slow increase in arc voltage is observed at this late stage of the fault. It is possible that this effect does not exist in the case of copper, which erodes at a much slower rate than aluminum. For very long-duration arcs at least, the cable may be cut by the arc, causing random changes in the arc-burning conditions and, hence, very unstable arc voltage.

5) In a few of the tests, we experienced a sudden arc transfer from one grounded electrode to another, some distance away. This results necessarily in an arc voltage increase, as seen in Fig. 8.1, where the sudden arc voltage increase was due to an accidental flashover to a remote grounded structure. The voltage drop on the arc section outside the splice is proportional to this section length and has a gradient of about 1500 V/m. Consequently, if the arc length in air is about 0.5 m, the arc voltage increase due to this arc section is about 750 V, almost equal to the arc voltage drop on the short arc section confined within the splice insulation. Obviously, if elongation of the arc occurs, the arc power will increase proportionally to the arc voltage increase and, depending on the fault duration after arc transfer, a significant additional amount of energy may be released.

In reply to Prof. T. Lipski's general comment regarding faults on aged connectors, we fully agree that this kind of fault may happen, possibly releasing considerable energy because of the long time lapse before the arc on the loosed connector degenerates into a powerful phase-to-ground arcing fault. However, the arc power developed by arcing on the connector alone is rather low and energy release is distributed over a long time interval so that risk of sudden pressure rise in the manhole due to this phenomenon is very limited. Nevertheless, we agree with Prof. Lipski's suggestion that a study of such arcs may be of great interest, although it should be preceded by an in-depth study of the aging phenomena of electrical connectors, especially fretting, which seems to be the primary cause of degradation.

With respect to the other four remarks by Prof. Lipski, we offer the following comments.

1) The "two-sided coils" in Fig. 6 are simply a schematic representation of the concentric neutral helically wrapped around the XLPE-insulated cables.

2) The existence of the post-arc voltage on sample recordings is due to the master switch in our laboratory being equipped with capacitors parallel to the main contacts so that, after it has been turned off and before a disconnecting switch opens, the capacitors remain energized in series with the capacitive divider used for arc voltage measurements.

3) There was a typing error: for type A splices the text should read: $V_{a,est} = 0.608 - 0.003I_a$ kV, and for high-current interfacial faults on type C splices: $V_{a,est} = 1.59 - 0.003I_a$ kV.

4) The deviation from flat-topped arc voltage for longer fault durations on XLPE-insulated cables is not as marked as one may think (see also our fourth reply to Mr. Buchholz). In addition, we observed a very regular, almost perfectly flat-topped, arc voltage for arcs several centimetres long in air (C-1). For much longer arcs in air (about 800 cm), the arc voltage becomes trapezium-shaped, with a somewhat higher instantaneous value at the beginning of each loop (2).

In response to J.P. Bhangu's two questions, we offer the following comments.

1) It is true that our investigation was limited to the 4-kA to 16-kA fault-current interval for which the arc voltage exhibits a flat-topped shape and has an almost constant mean value, depending on the faulted equipment only. Any extrapolation, therefore, must be considered hypothetical until experimental confirmation is obtained. Nevertheless, there are indications that extrapolation is acceptable in the current range from about 1 kA to 20 kA. This conclusion is based on many recordings taken under asymmetrical-fault conditions, where a virtually identical flat-topped arc voltage was observed for both major and minor loops of the arc current, especially after the first two loops (see also our first reply to Mr. Buchholz). Recently, we obtained new evidence for 2-kA faults on type E splices, allowing us to extend our conclusions to rectangular waveshapes and practically constant values of the arc voltage for the lower fault-current range (at least for type E splices).

2) With respect to the influence of the high circuit power factor on the arc voltage value and shape, we consider it to be negligible. One reason is that, in steady state or for symmetrical faults, the arc voltage is almost independent of the instantaneous value of the arc current. Another reason is that for faults with high PF the aperiodic component is dumped very quickly and any fault that occurs may always be considered symmetrical. Consequently, the differences in arc voltage due to the high PF value can be neglected. In contrast, a very high PF value could influence the fault-current value and shape, although for 25-kV systems the effect would only be moderate (see also Chap. 4 in Ref. 2).

In answer to R. Frank's remarks, a distinction should be made between mean arc voltages of relatively low value and spikes observed on the arc voltage curve. The latter almost always appear near the natural arc-current zero crossing and are nothing more than the initial portion of the transient recovery voltage in the time interval between arc extinction and restrike. Consequently, the influence of these spikes on the arc power and energy is rather negligible. The shape of the spikes depends on the circuit parameters and, also, on the immediate arc environment, as may be concluded from Mr. Frank's comment.

As for his second remark, the existence of a metallic shield of closely wrapped wires helps to keep the arc voltage at a constant value. The significance of this effect should not be exaggerated, however, because the largest fraction of the arc voltage, except when a long section of the arc is in air, is due to the intense cooling of the arc in the discharge channel in the cable or splice insulation. Nevertheless, in the case of faults on splices, it is recommended that a concentric-neutral bypass be installed close to the splice to limit the outside length of the arc and thus hold the arc voltage at its lowest possible level.

J.F. Smith's remarks on the small quantity of polymeric insulating materials decomposed by the fault arc confirms our own observations. The only exception is the case of faults on PILC splices where a large quantity of insulating compound may decompose into several by-products whose subsequent combustion may produce a considerable amount of heat that contributes heavily to pressure rise in a closed vault (2). On the other hand, in the case of faults on secondary underground cables in ducts, the arc-induced pyrolysis of adjacent organic materials may be a major cause of subsequent manhole explosion (C-2).

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