INTERRUPTING PERFORMANCE OF POWER EXPULSION FUSES RENEWED

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Summary

This paper presents laboratory test results of testing power fuse units renewed from which its behavior can be predicted theoretically considering the basic parameters like the cylindrical geometry and dimensions of its arcing chamber made of boric acid.

In practice it has been observed during many years that after operation by low overcurrents, the length and radii of that chamber do not suffer any significative increase of its dimensions, reason for which was decided to undertake this basically experimental study.

1 Introduction

The Mexican utility Luz y Fuerza del Centro(LFC) supply electrical energy to the Central Area of México inside of which is located the biggest City of the World. The total number of users is about 4,622,000 that during 1994 consumed 23,788 GWh.From the standpoint of distribution of electrical energy in medium voltage LFC has an overhead radial network system mainly in the voltage level of 23 kV with 507 primary feeders and 12,723 Km of three phase circuits feeding 33,000 pole type distribution transformers.

The protection against overcurrent of this system is given applying circuit breaking devices like circuit breakers, reclosers and expulsion K type fuses. The most extensively kind of applied fuses are: the power type with interrupting capacity of 12.5 kA sym. rms and distribution type with interrupting capacity of 7.5 kA sym. rms.

Approximately each year operate 27,800 expulsion fuses of different current ratings, being about 22,400 power fuse units of 3A type K.

Because of the majority of overcurrent presented are overloads and high impedance short-circuit secondary currents, about 16,000 (71.4%) of them are renewed annually and remainder(28.6%) are rejected.

During 12 years it has been observed that under the above indicated operating conditions the internal components of the fuse units such as the arcing chamber and electrodes do not suffer any perceptible erosion and the transfer bridge, tulip contact and compression spring do not experiment any physical and dimensional variation. Therefore in the beginning it was supposed the possibility to reuse the fuse units previously operated by overload and secondary faults without running any risk.

2 Description of interrupting process

The arc in the expulsion fuse depends for its extinction upon an intense blast of gas generated by sublimation of the inside wall fuse tube and increased in intensity as the arc currents increases. When this happens the arc fills the tube and ablation of the wall material results. The arc then burns inside a plasma whose components are derived from the ablated vapor[1]. The pressure inside the tube is increased by the mass influx from the wall and in a given instant the plasma is expelled from the tube at the outlet.

In this transient process the success or failure of current interruption depends on the race between the speed of recovery of dielectric strength of post-arc space and transient recovery voltage between arcing electrodes.

An useful measure of the ability of an interrupting medium to recover its dielectric strength after current zero is the time constant for the arc.

Mayr[2] described such a behavior by this differential equation:
dQ/dt= EI-No (1) ; Q stored energy in the arc per unit lenght; No rate of loss of energy per unit length; E arc voltage; I arc current.

He assumed that during the transient period the diameter of the arc column remains esentially constant. The electrical conductivity of gas is given by $\sigma = k \exp(q/q_o)$ (2); k and q_o are constants; q = specific energy content in the gas.

The arc resistance R per unit length is given by R= const. exp (- Q/Qo) (3) ; this equation can be rewritten as dQ/dt = - Q/R dR/dt (4); since R = E/I, I = f(t) and E = R f(t); then (4) becomes

$$\frac{dQ}{dt} = -\frac{Q_o}{R}\frac{dR}{dt} = \left(\frac{d}{dt}\right)\frac{1}{R} + \frac{N_o}{Q_o}\frac{1}{R} = \frac{1}{Q_o} f^2(t) \quad (5)$$

Thus the time constant of the arc is defined as Θ = Qo/No (6) ; Qo and No must be measured for any given arc.

Frind [3] extends this concept by using the relationship between the electrical conductivity and the flux function derived by Maecker[4] and for a conduction cooled arc he obtained $O = r_o^2/(2.4)^2 k$ (7) ; r_o = radius of the arc ; k = thermal diffusivity

2.1 Critical current density

The predominant influence of the arcs confined by a wall is the ablation of wall materials resulting in high pressure inside the tube and high plasma velocities near the outlet.

The maximun power that can be conducted through the stabilising wall is given by:

$$P_{max} = \frac{2\pi R\, K_w T_s}{t_w} \quad (8)$$

R wall radius; k_w thermal conductivity; T_S sublimation temperature;
t_w wall thickness;

The ohmic power

$$P_{\Omega} = \frac{I}{\pi R^2 \sigma} \qquad (9)$$

I current; σ electrical conductivity

By comparison between equation (8) and (9) we obtain:

$$\text{current density} = \sqrt{\frac{2\sigma K w T_s}{R\, \tau_w}} \qquad (10)$$

From this equation we can observe: If R is kept essentially constant the current density j will keep up a high magnitud and there will be an excess of energy which is dissipated by sublimation of the wall material.

It has been found [5] that the critical current density is of this order: $j = 700\ A/cm^2$. That behavior implies a pressure rise in the confining channel.
In the case of power fuses under study on have a basic cylindrical geometry of the arcing chamber as is indicated in figure 1.

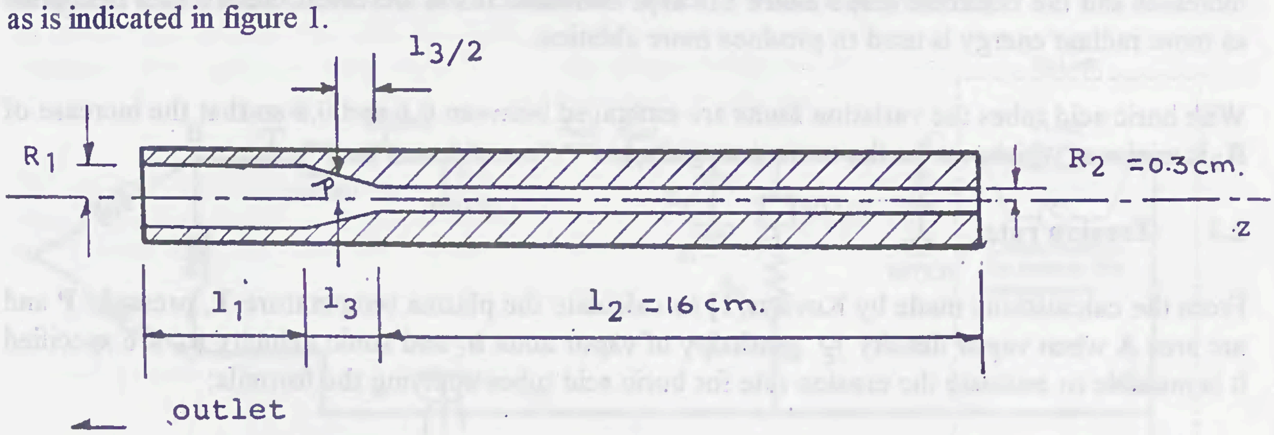

Figure 1. Basic geometry of the cylindrical acid boric arcing chamber studied.

Under short circuit conditions the chamber 1 of radius R_1, chambers 2 of radius R_2 and the conical chamber 3 of length l_3 work together and therefore the overall surface ablating area is:

$$A_T = 2\pi\left(R_1 l_1 + R_2 l_2 + \rho l_3\right) \qquad (11)$$

Under overload and high impedance short circuit conditions, the surface ablating area is: $A = 2\pi R_2 l_2$ (12).
In this case the available area for transport of the ablated mass out of the channel is $Q = \pi R_2^2$ (13)

It is evident that: $2\pi R_2 l_2 v_r > \pi R_2^2 v_e$ (14)
where: v_r = radial velocity and v_e = exit velocity. Near the outlet: $v_z > v_r$

But for a significant portion of the axial flow $v_z \approx v_r$ [5]

As there is a sonic limitation on the axial velocity, the pressure drop can not be from central pressure to ambient and is limited to : $p_e / p_c \doteq 0.5$

The critical parameter that defines the magnitude of the overpressure is the ratio of channel surface to cross-sectional area :

$$c.p. = 2\pi R_2 l_2 / \pi R_2^2 = 2 l_2 / R_2 \quad (15).$$

As it has been found on about 30,000 renewed fuses operated by overload and high impedance short-circuit currents, the increase of radius $\mathbf{R_2}$ is insignificant and therefore the tube area remains practically constant, the length $\mathbf{l_2}$ do not experiment any variation.

Under such a condition $\mathbf{l_2 >> R_2}$ when comparing the performance of a new power fuse against a renewed one,the plasma pressure is of the same order causing plasma to de ejected from the tube at the outlet.

From calculations of Kovitya and Lowke [6] it is shown that the axial gradient of arc area $\partial A/\partial z$ is small and can be neglected. Kovitya[1] using the isothermal approximation calculated the arc behavior for different ablating materials.

For instance the ratio between arc area **A** to tube area **Q** decreases slightly when the current increases and the radiation scape factor f is kept constant. If f is increased the arc area decreases as more radiant energy is used to produce more ablation.

With boric acid tubes the variation limits are embraced between 0.6 and 0.8 so that the increase of $\mathbf{R_2}$is minimun whichever be the current magnitude.

2.2 Erosion rate

From the calculations made by Kovitya[1] to calculate the plasma temperature **T**, pressure **P** and arc area **A** when vapor density ρ_c , enthalpy of vapor zone $\mathbf{h_c}$ and sonic velocity $\mathbf{a_c}$ are specified it is possible to estimate the erosion rate for boric acid tubes applying the formula:

$$\text{erosion rate} = \frac{\dot{m}_c}{EI} = \frac{f}{h_c}$$

$\dot{m}_c$ rate of wall ablation, E electrical field, I current applied; f radiation scaping factor (fraction of the total radiation that is not absorbed by the vapor zone,h_c enthalpy of vapor zone).

The boric acid properties at 3000 K calculated by Kovitya[1] are vapor density = 0.1226 Kg/m
a_c sonic velocity = 964.4 m/s, h_c enthalpy 8 kJ/g, f = radiation scape factor ≈2.

Applying the formula (16) we obtain: **erosion rate =0.025 g/kJ** for acid boric tubes with **l** = 20 cm and **R** = 0.5 cm and currents comprised between 1 to 15 kA.

Hettwer[7] using a clyndrical sample of **l** = 2.5 cm and **R** = 0.625 cm, applied an underdamped current of 2 kA at 225 Hz, found for acid boric material an erosion rate 0.026 g/kJ .

In the case of the power fuse units studied, when considering the short circuit currents of 3.14 kA and 11.1 kA and taking into consideration the condition $\mathbf{l_2 >> R_2}$, using the chart of fig. 6 of Kovitya's document[1], it is possible to make calculations.

In our case considering, $\mathbf{l_2}$ = 16 cm and $\mathbf{R_2}$ = 0.3 cm **Q** = 0.28274 cm^2 $l_2/R_2 = 53.333$

First case: Applying 3.14 kA
$(I/Q)\sqrt{R_2}$= 6082.5 A/cm ; plasma temperture T≃15,000 K; pressure P≃100 atm

Second case: Applying 11.1 kA
$(I/Q)\sqrt{R_2}$= 21,502 A/cm ; plasma temperture T≃26,000 K; pressure P > 100 atm

In both cases the pressures attained are very high[8] after the vaporization of the fuse wire. Under this condition the interruption is absolutely satisfactory as it was demonstrated by the interrupting tests described in the next section.

3 Tests

In order to verify the theoretical predictions sketched in the previous section and the results found in practice, we carried out interrupting test on the power fuses renewed for us. These tests were made complying with the requirements of ANSI C37.41-1988 Std. series 2, 4, 5 and 6 of table 2 [10]. Tests were carried out at rated maximun voltage of 23 kV. Power frequency recovery voltage was maintained across the fuse terminals for at o.5 second after current interruption.

In figures 2 and 3 are shown the tests circuits for series 2, 4 and 6 respectively.

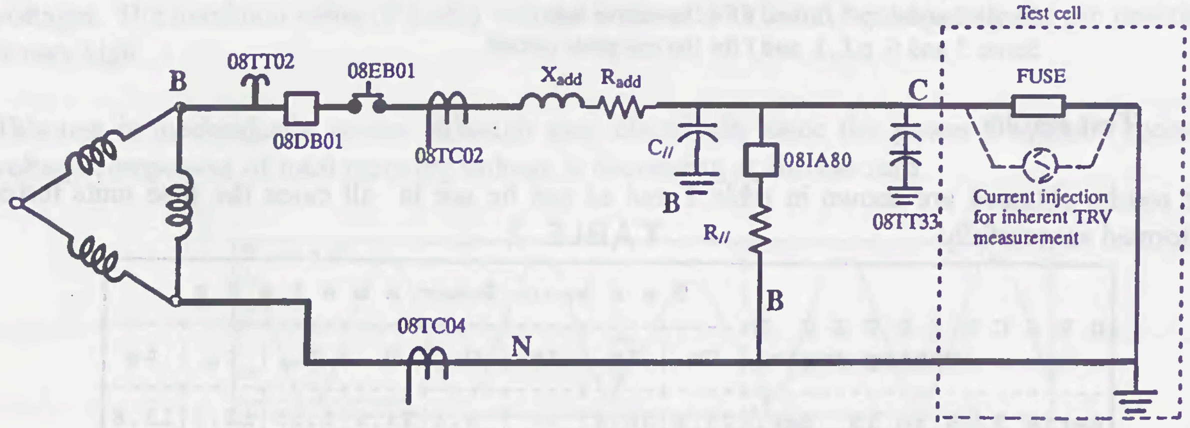

Figure 2. Test circuit for series 2 and 4

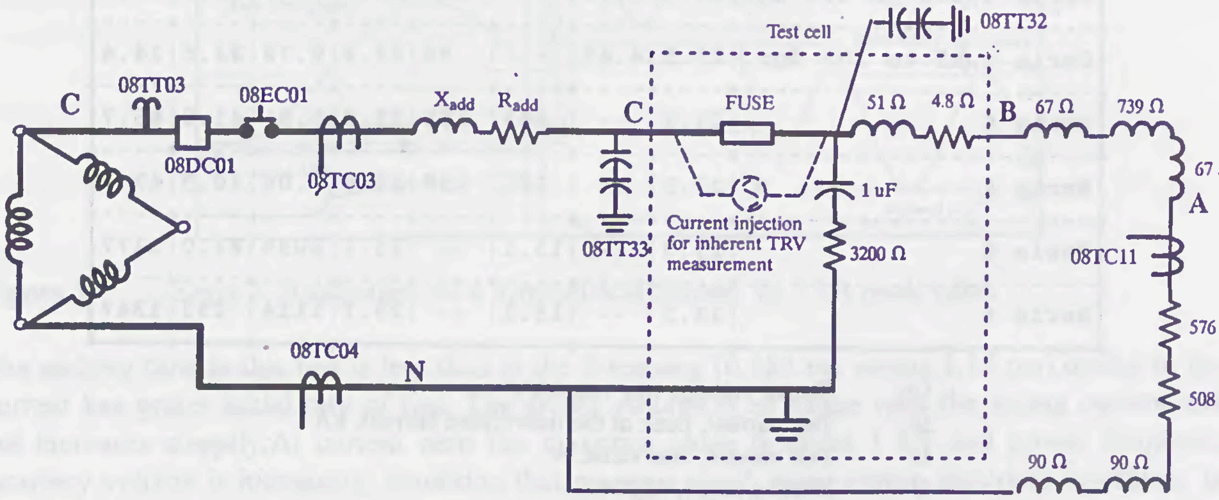

Figure 3. Test circuit for serie 6

In table 1 we show calibration test and measurements of prospective TRV.

Test circuit for	Us	Îe	Ie	X/R	Prospective TRV p.f.	Prospective TRV t_2	Prospective TRV f
Serie 2	23.2	28.9	11.1	17	1.43	223	2.24
Serie 4	23.2	8.08	3.14	16	1.40	225	2.22
Serie 5	23.1	1.07	0.434	9.9	1.69	47	10.6
Serie 6	23.2	0.023	0.015	1.2	1.48	435	1.15

TABLE 1. Calibration test and measurements of prospective TRV

Us Source voltage, rms value, kV
Îe Test current, first asymmetrical peak, kA
Ie Test current, rms value, kA
p.f. Peak factor
t_2 Time to peak, ms
f Equivalent frequency, KHz

For prospective TRV
Series 2 and 4: p.f., t and f for the source side
Series 5 and 6: p.f., t and f for the complete circuit

3.1 Test results

The results obtained are shown in table 2 and as can be see in all cases the fuse units tested performed successfully

TABLE 2

DESCRIPTION (Making angle)	Us	Îe	Ie	O	U	t_m	t_a	t_e
Serie 2,(-5 to 15 dgr.)	23.4	28.6	--	4.1	23.2	1.13	12.7	13.8
Serie 2,(85 to 105 dgr.)	23.4	16.6	--	88	23.2	0.38	16.1	16.5
Serie 2,(130 to 105 dgr)	23.5	25.4	--	137	23.3	0.47	14.9	15.4
Serie 4,(85 to 105 dgr.)	23.5	4.67	--	90	23.3	0.78	23.6	24.4
Serie 5	23.3	--	443	155	22.9	5.8	41.0	46.7
Serie 5	23.3	--	441	138	22.9	7.06	40.5	47.5
Serie 6	23.3	--	15.1	--	23.1	1094	83.0	1177
Serie 6	23.3	--	15.1	--	23.1	1114	233	1347

Us Source voltage, rms value, kV
Îe Test current, peak of the interrupted current, kA
Ie Test current, rms value, A
O Making angle, degree
U_{60} Power frequency recovery voltage, kV
t_m Melting time, ms
t_a Arcing time, ms
t_e Total clearing time, ms

From series 2 and 6 we present at least one oscillogram with the corresponding description:

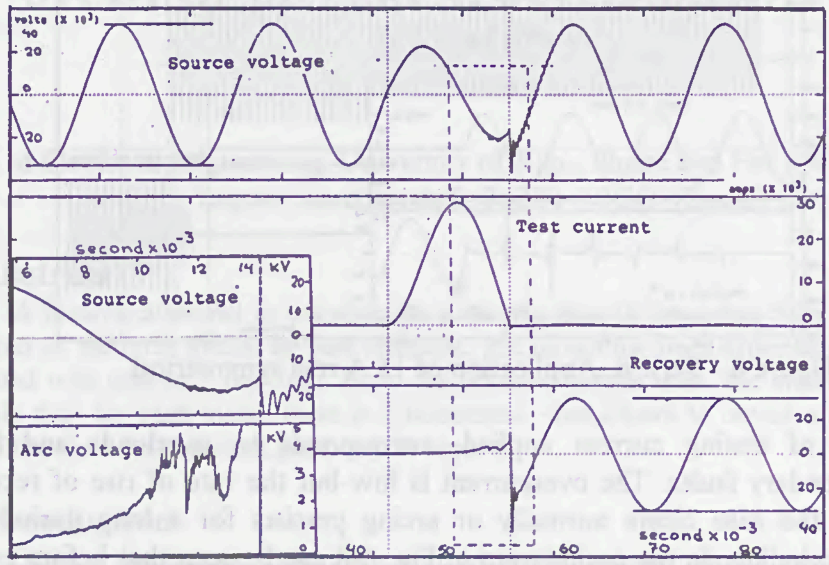

Figure 4.- Serie 2. Application of a fully asymmetrical current of 28.5 kA peak value

In this case after the current passes through its peak value the arc voltage begins to increase faster an before the current zero this arc voltage increases steeply and then decreases appearing spikes voltages. The maximun value of arcing voltage is about 10 kV and consequently the arc resistance is very high.

This test is mechanically severe although easy electrically since the power frequency recovery voltage component of total recovery voltage is decreasing at current zero.

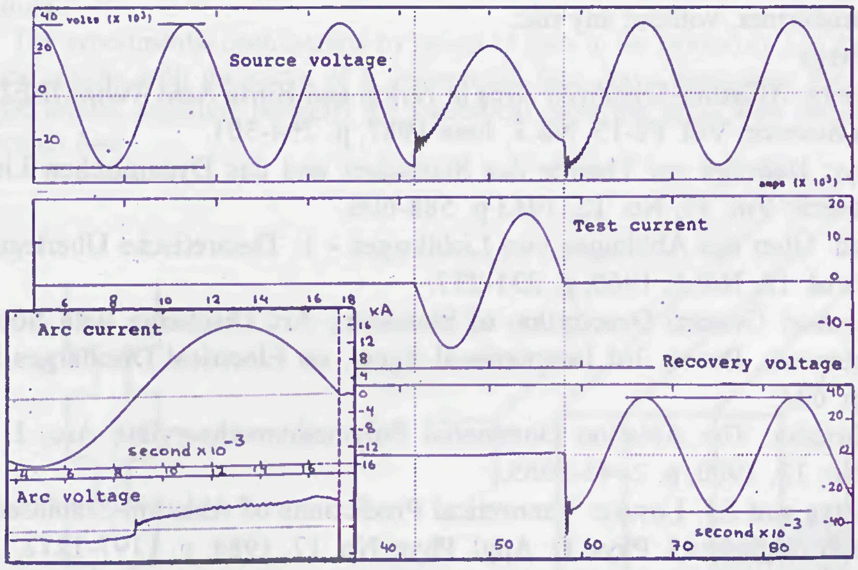

Figure 5.- Serie 2. Application of a symmetrical current 16.5 kA peak value

The melting time in this test is less than in the foregoing (0.383 ms versus 1.13 ms) owing to the current has grater initial rate of rise. The arcing voltage is en phase with the arcing current and not increases steeply.At current zero the maximun value is about 1 kV and power frequency recovery voltage is increasing, condition that means a much more severe electrical condition. In this case, if the arcing chamber radii (Fig.1) were enlarged the likelihood of failure could be greater. Nevertheless the result obtained was satisfactory.

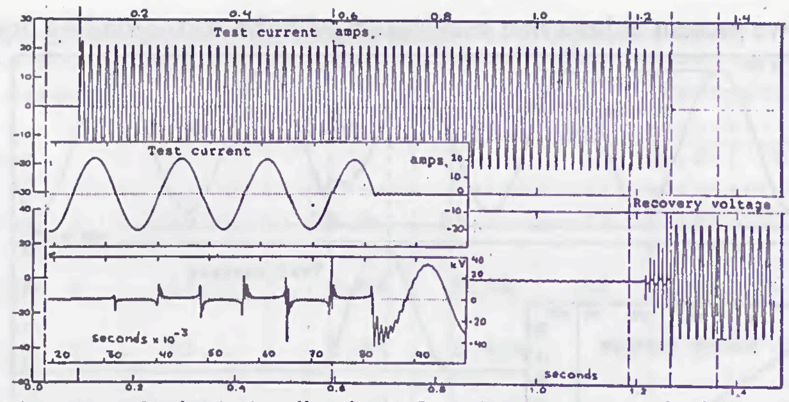

Figure 6.- Serie 6. Application of 15 A rms symmetrical

The magnitude of testing current applied, corresponds to overloads and high impedance transformer secondary faults. The overcurrent is low but the rate of rise of recovery voltage is high and either the fuse clears normally or arcing persists for a long period of time failing thermally and exploding. In the oscillogram of Fig. 6 it can be seen that before each current zero the arc voltage increases to values as high as 40 kV. This means that at the final current zero the rate of increase of resistance of the dynamic arc is enormously increased and so the arc becomes much more effective in opening the circuit.[9]

4 Conclusions

As it has been demonstrated with the interrupting tests made at the High Power Laboratory of IREQ, the results found in practice and the theoretical predictions outlined in Section 2, it is quite possible to renew these power fuse units operated by overload and short circuit secundary faults provided are satisfied some basic mechanical requirements not presented in this document, therefore, they can be applied in protecting against overcurrents, the primary side of pole type distribution transformer, without any risk.

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