REVIEW

Frequency Acceleration of Voltage Endurance

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ABSTRACT

Frequency acceleration of voltage endurance has been the subject of a large number of research papers. A review of those papers reveals that it is not a priori possible to rely upon obtianing linearity of acceleration. It is shown that the appropriate acceleration factor for micaceous insulation can only be determined with very long term testing.

INTRODUCTION

At a meeting of the AC Life Sub-committee of G32 in January 1977 it was decided that certain specific reviews of the literature should be undertaken. The purpose of such reviews is to 1) assess the state of the art in various aspects of ac life testing, 2) define the need for additional research effort to be done by G32 technical committees, 3) evaluate the extent to which standard test procedures can be arrived at. A discussion of how this review relates to these objectives is included in the conclusions of this paper.

The specific topic assigned to this review is that of voltage endurance acceleration by means of increasing the frequency of the applied test voltage. An excellent review of voltage endurance testing was presented by Olyphant and McKeown in 1963 [1]. Those authors reviewed effects of temperature, different electrode geometries, mechanical stress, ambient humidity and test frequency. In their earlier reviews [1] Olyphant and McKeown concluded that all of these factors could alter the life of materials under corona and also their relative rank. As will be shown in this review, little has transpired to change that conclusion in the succeeding 15 years. There is still no way to predict the effect (or in some cases the direction of the effect) of variations of the physical parameters associated with high frequency voltage endurance testing. We have not attempted in the review to resummarize that earlier work but rather to cite only the more definitive papers prior to 1963 and concentrate on a more complete commentary on papers published since 1963.

There has been no intention to eliminate any significant piece of work in preparing this review. To the extent that such omissions have occurred, we hope that those who comment on this paper will help us to correct these errors.

HIGH VOLTAGE STATOR INSULATION

One of the earliest discussions of voltage endurance testing of armature insulation by means of frequency acceleration of the applied voltage was written by Rhudy and Mazanek [2]. They pointed out that both chemical degradation and localized erosion due to corona pulses can be operative. They further observed that only the discharge erosion mechanism can be proportionately frequency accelerated. The experimental studies were done on formed coils.

Ryder et al. [3] tested a number of different epoxy mica systems in a sample configuration which contained internal voids. The tests were done in both helium and nitrogen. The damage done in helium was much less than that done in nitrogen. These authors stated that acceleration up to 1200 Hz is "realistic". It is not clear from their paper, however, that this conclusion is based on actual failure data. Rather, their acceptance of linear frequency acceleration seems to rest on a determination that the pulse size distribution is the same at higher frequency as it is at 50 Hz. In addition, the loss tangent was found to be constant between 50 and 500 Hz.

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Sections of armature bars were tested at 412 Hz in both air and hydrogen and the results were reported by Breitenstein et al. [4]. The observed life in hydrogen was four times longer than in air at the same applied voltage stress. In a theoretical section of the paper, it was noted that the pulse size is a function of the overvoltage which in turn is determined by the statistical time lag and the rate of rise of the applied voltage. The effect of changing rate of rise of voltage and change of statistical time lag approximately cancels each other. The pulse size and number of discharges per cycle are therefore expected to be constant in the frequency range of 60-412 Hz.

Wichmann and Gruenwald [5,6] have investigated the possibility of accelerated testing in epoxy-mica armature bar insulation. The specimens were clamped between cooling plates during high voltage testing. The effects that were observed due to temperature variation will be discussed below.

A CIGRE Conference paper [7] reported a voltage endurance program on stator coil simulated electrodes of solid copper bars with corner radii of 1 mm. The test insulation consisted of glass-mica paper impregnated with an epoxy.

CABLE INSULATION

Perhaps the earliest work which was done on frequency acceleration was done on cables. P. R. Howard's early and excellent paper [8] examined failure data taken on different cable diameters at different applied voltages. Howard investigated frequency of applied voltage up to 900 kHz as well as recurrent unidirectional dc voltage cycles. He also measured pulse size and proposed a relationship between life and pulse size (see "analysis" section).

Mason [9] carried out an experimental study of polyethylene using voids of different configurations. He observed significant effects due to the kind of metal used for the test electrode. Brass was found to produce carbonization unlike steel or platinum. He found that voids bounded on one side by metal erode faster than voids completely surrounded by dielectric material.

Starr et al. [10] tested polyethylene cables for voltage endurance. Special emphasis was placed on the need for proper termination to avoid in-leakage of air.

Noto and Hiroshima [11] have tested Mylar and polyethylene using a rotating electrode. They used this test method in an attempt to reduce the variation in failure time. They were able to produce a random pattern of failure points. Several combinations of electrode area and series air-gap were investigated.

Noto and Yoshimura [12] have made specimens of polyethylene with encapsulated needle electrodes. The needle electrodes were encapsulated both with and without an air gap at the base of the needle. The time required to initiate "treeing" was observed. In specimens without a cavity, it was shown that tree growth rate goes through a maximum for increasing applied voltage at constant frequency. This was explained by Noto and Yoshimura as being due to a buildup of gas pressure which chokes off discharges. At still higher voltages, the dielectric heating is sufficient to allow gas to escape and the rate of tree propagation again increases with increasing voltage.

A multi-laboratory set of comparison experiments has been reported by Toriyama et al. [13] on polyethylene. Fourteeen different investigators used two different types of electrodes. The variation between one investigator and another was as large as the effect of going from a test voltage of 3 kV to 5 kV for a single investigator. Toriyama et al. discussed several factors which may contribute to the large dispersion of the data such as relative humidity and air flow. A further analysis of this paper is given in the section on "linearity of acceleration".

The growth of trees in cross-linked polyethylene was studied by Densley [14]. He discussed three different failure regions. He determined these distinct regions in two ways: 1) the presence of inflections in the probability distribution of failure vs. time, 2) the observation of three different structural forms of trees.

Dunbar [15] studied the effect of helium-oxygen atmospheres on wiring and cabling components. The voltage endurance work was done at 400 Hz of applied voltage. Apparently this was the anticipated frequency of application of these space vehicle components. No comparisons were made with life obtained at other frequencies.

OTHER MATERIALS

An extensive investigation of the effect of relative humidity on polyethylene, polystyrene, and polyethylene terephthalate was reported by Hewitt and Dakin [16]. They showed that failure time decreases with lower relative humidity and they rationalized their observed temperature dependence of failure through this humidity effect.

A number of cast epoxies were tested by M. Olyphant [17] who found that they gave rise to different response to frequency acceleration. He hypothesized that the greater time available for space charge diffusion at lower frequencies gave rise to greater cycle-to-cycle field enhancement and consequently lower time to failure at the lower frequencies.

In a study unrelated to the above, Olyphant [18] reported on 1600 Hz tests on varnished cambric, varnished polyester mat, and an epoxy cloth.

A discussion by Cameron [19] disclosed the successful frequency acceleration for voltage endurance testing of a phenolic paper bushing. Hayworth [20] tested capacitors made of polyester film in which reversal of the voltage across the device was accomplished at frequencies up to 200 kHz.

Extensive studies of failure with an artificial cavity have been carried out by Okamoto et al. [21]. The cavity was either sandwiched between two films or, in the case of thick sheet specimens, it was machined on one side. The range of materials tested included: polyethylene, polyethylene terephthalate, polycarbonate, polypropylene, cellulose triacetate, polyamide, polyfluoroethylene, polypropylene, and polyimide. The frequencies of the applied test voltage were 50, 60, 400, 500, and 600 Hz. A large scatter of the data was attributed to a number of experimental factors such as specimen preparation and electrode application.

Reynolds [22] aged samples of silicone rubber under corona using 600 Hz applied voltage. The silicone samples were compared with asphalt-mica specimens but no direct comparison with life at 60 Hz was attempted. The study showed that the conducting salt which accumulates due to discharging is responsible for the increased power loss and that the loss returned to that of an untested specimen when these conducting deposits were removed.

ANALYSIS

Several interesting approaches to the analysis of frequency accelerated voltage endurance data have been examined. Howard [8] showed that a wide range of cable diameters can be rationalized on a single graph by plotting the ratio of the test voltage to the voltage necessary to produce a minimum discharge size for damage to occur. For his specimens this minimum discharge size was 2×10^{-12} C. When a different choice of "minimum voltage" was made, the different diameters were not rationalized. Mason [23] on the other hand chose to use a ratio of V/V_i where V_i is the inception voltage. In a separate report [9] he indicated the "safe" discharge level must be considerably lower than 2×10^{-12} C.

Rhudy and Mazanek showed one of the first applications of Weibull statistics to voltage endurance [2]. This was carried further by Breitenstein et al. [4] where it was shown that the characteristic slope of the Weibull distribution is the same at the higher frequency as at the lower frequency in the range of stress where valid frequency acceleration was obtained.

Carlier et al. [7] stated that their failure data may be fitted to either Weibull, normal, or log normal statistics. They also stated that the distribution seems to divide into two distinct populations. However, with so few data points as they have shown, it does not seem possible to be firm on either of these two conclusions.

Mitsui and Inoue [24] presented a paper which does not deal with frequency acceleration but does contain a very large quantity of voltage endurance failure data which may be used to answer the question of which statistical distribution is favored. They concluded that Weibull statistics give the highest correlation coefficient.

TEMPERATURE EFFECTS

One of the most important concerns of many investigators of this accelerated frequency testing has been that of temperature effects. Clearly the dielectric heating goes up directly with the frequency of the applied voltage. Thus, if electrical time to failure is temperature dependent, and if dielectric heating is significant, one might expect nonlinearity of acceleration due to heating.

Mason [28] has shown an increase of time to failure at constant stress, for decreasing temperature for several different laminates. Starr and Agrios [10] have stated that an increasing temperature decreases time to failure for polyethylene cables. The functional form of the temperature dependence was said by them to be Arrhenius with increased variability at the higher temperature. In a discussion of tests on polyethylene encapsulated needles Noto et al. [12] hypothesized that gas buildup at higher temperature can be mitigated by diffusion.

In two separate papers [5,6] Wichmann and Gruenwald have discussed the use of cooling plates to control temperature effects. It is interesting to note that for their stator insulation material, increasing temperature has a beneficial effect. However, it is not clear to the authors of this review that the temperature effect they cite is significant to within the scatter of the data.

Carlier et al. [7] found that a micaceous armature insulation exhibited 10 times greater time to failure at 120°C than at room temperature. There is a considerable analysis and discussion of temperature effects in Reference 7 which is outside the scope of this review to paraphrase. The essential element in their analysis is the role of temperature in determining pressure buildup and the release of that pressure by diffusion out-gassing.

LINEARITY OF ACCELERATION

Table 1 presents a summary of the experience which various investigators have had with respect to linearity of frequency acceleration. In the last column is listed a comparison of the number of cycles to failure at high test frequency compared with the same quantity at the lower test frequency. Clearly when the number of cycles to failure at the two frequencies are the same, linearity of acceleration has been achieved. Where the investigator has assigned a reason to attainment, or lack therof, of linear acceleration, this is indicated in Table 1.

Densley [14] hypothesized that different kinds of trees grow in different voltage regions and this effect gives rise to greater or lesser frequency acceleration. Hewitt and Dakin [16] attribute their observation of nonlinearity to the heating at higher frequency. They separately show that time to failure decreases with lower relative humidity. Olyphant [17] associates early tree formation with nonlinear acceleration.

One of the largest data bases in the literature is that reported by Toriyama et al. [13]. In that study, a number of different test frequencies were converted to the equivalent 50 Hz time to failure on the assumption that the test time can be linearly accelerated with frequency. Table 2 is an average of their data for times to failure observed at the different test frequencies. The test configuration called electrode (a) was a noncontacting hemisphere-to-plane. Electrode (b) was a contacting cylinder-to-plane. The first column of Table 2 is the number of observers who had performed the test at the stated frequency; in this table, all observers were weighted equally in obtaining the average. It seems clear from Table 2 that the assumption of linear frequency acceleration is not well justified particularly for electrode (b).

Table 1

Experience in obtaining linear frequency acceleration

Reference	Material	Frequency Range, Hz	Ratio of Cycles to Failure at High Test Frequency to Cycles to Fail at Low Test Frequency
Hayworth [20]	Polyester	30 kHz	=
Olyphant [18]	Varnish cambric Polyester mat Epoxy cloth	1600	= for dry ambient
Okamoto [21]	Void between films	600	
Toriyama [13]	Polyethylene	50-10,000	Assumed = See Table 2
Wichmann [6]	Epoxy Mica	50-40,000	= up to 1000 Hz
Wood [3]	Epoxy Mica	1200	"realistic"
Breitenstein [4]	Micapal	412	= (at stress) < 150 vpm
This paper	Micapal	412	>
Wichmann [6]	E-Mica	50-500	" = "
Starr [10]	Polyethylene	60-10,000	=
Rhudy [12]	Coil (formette)	60-3,000	=
Cameron [19]	Paper Brushing	100 kHz	=
Howard [8]	Polyethylene	900 kHz	=
Hewitt [16]	Polyethylene Styrene Terephthalate	3,000	< Humidity effect
Olyphant [17]	Cast Epoxies	1,400	> With early tree formation
Carlier [7]	Epoxy-glass-mica	400	=
Noto [12]	Polyethylene-needle	50-10,000	= To tree initiation
Densley [14]	Polyethylene	60-800	≷ Voltage dependence of tree type

Table 2

Analysis of data published by Toriyama [13]

N	Freq. Hz	Electrode (a) (hrs)			Electrode (b) (hrs)		
		3 Kv	4 Kv	5 Kv	3 Kv	4 Kv	5 Kv
6	50-60	255	129	68	120	59	36
3	450-500	311	120	61	148	73	40
5	1000	310	136	70	150	89	52

GENERAL ELECTRIC EXPERIENCE

General Electric has experienced many years of successful application of an epoxy-resin insulation for armature bars. This has been applied on both large and medium steam turbine generators at the Schenectady and Lynn manufacturing facilities. Both during the development and throughout the years of application of this system, numerous voltage endurance studies have been carried out at the laboratories in both locations. An examination of these data is shown in Figures 1 and 2.

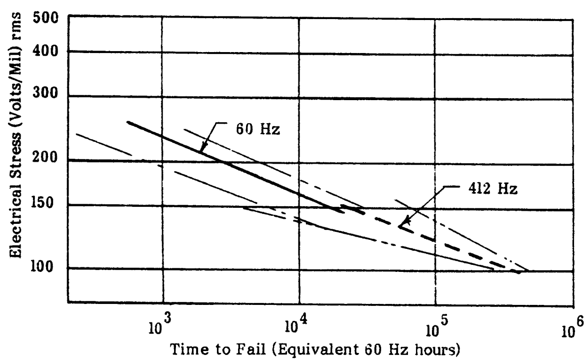

Fig. 1: Voltage endurance using silver painted electrodes.

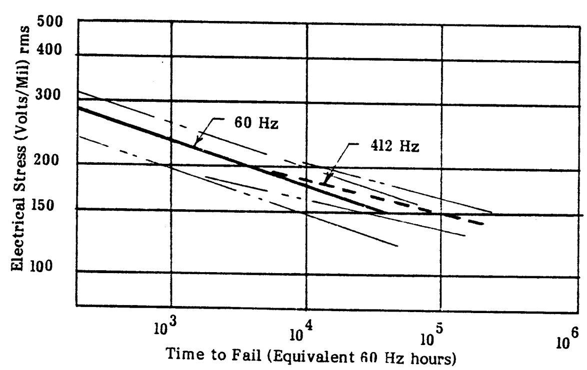

Fig. 2: Voltage endurance using generettes showing the mean Weibull and (95%) limits.

These figures represent the data from both laboratories using laboratory specimens of this insulation system. There is some variance between the two investigations owing to differences in electrode length. This variation has been corrected to obtain the above figures. The Weibull hazard for one electrode length is modified by the ratio of that electrode length to the second electrode. The range of the data which is shown in the above figures represents the 95% probability limits. These were derived from the 97-1/2 percentile and the 2-1/2 percentile values obtained from the Weibull distributions. The center line is a regression line through the 50th percentile of the Weibull distribution.

An earlier examination [4] of the comparison 60 Hz and 412 Hz testing was based on testing times of up to approximately 8000 actual hours. At that time it was thought that good linearity of acceleration was being obtained. More extensive testing, out to 66000 actual hours has shown that this agreement only existed at lower testing times. Long time testing at 412 Hz has shown a longer than expected time to failure at the lower values of applied stress. It is difficult to compare 412 Hz failure data at low stresses and very long times since only a few 60 Hz data are available in that region. For example, failure data at 120 vpm (volts per mil) (47.2 kV/cm) at 60 Hz would be obtained only after 7 years. Conversely, we have previously stated [4], and the test results continue to show, that a comparison at>150 vpm, (59.0 kV/cm) is not valid. However there is growing evidence that testing of armature bars in generettes [24] may allow the use of 412 Hz at stresses greater than 150 vpm.

It should be noted that differences other than electrode length exist between the two investigators. Small differences in test temperature and bare bar structure can also account for differences in the data. In spite of these uncertainties, we conclude that the acceleration factor is not the 6.9 ratio one would expect based on the frequency ratio. Results of these studies indicate an acceleration ratio in the range of 5.

Yet a different epoxy-mica system [26] which has been tested in these two laboratories appears to yield an acceleration factor which is almost equal to the ratio of the test frequencies. It is hoped that these additional data will be the subject of a future report.

CONCLUSIONS

1. Increasing test temperatures have been shown to be both beneficial and adverse to life depending upon the system on test. An increasing test frequency can give rise to increasing electrode temperature. This effect on linearity of frequency acceleration will be different for different insulation systems. Clearly, a controlled and constant electrode temperature is desirable in the absence of data which show an insensitivity to temperature.

2. Weibull statistics describe both power frequency and accelerated frequency voltage endurance failure data.

3. To the estent that any evidence exists, the effect of increasing relative humidity is to invalidate the linearity of frequency acceleration.

4. One cannot assume a-priori that voltage endurance can be linearly accelerated with increasing frequency. While the assumption of linearity is generally valid, there are numerous exceptions in the literature. It is therefore necessary to empirically determine the acceleration factor for each specific set of experimental conditions and each insulation system.

5. Because of the above conditions, it would be inappropriate to attempt to standarize high frequency voltage endurance testing.

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