A new method of estimating the inverse power law ageing parameter of XLPE based on step-stress tests

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***Abstract-* In recent years, HVDC cables have been greatly improved, 500kV XLPE DC cable has been developed, and many XLPE DC cables of lower applied voltage have been used in HVDC systems. However, there still is not a unified standard for testing high voltage DC extruded cable systems, only a recommendation. Furthermore the recommendation only gives a lower limit of ageing parameter (n=10 in the inverse power law $t_L \cdot V^n$= constant), which directly determines the voltage used in the test. A more precise value of ageing parameter is needed in order to improve the testing method. The most common method of estimating the ageing parameter uses constant-stress tests at different voltages (fields) and is based on the inverse power model, but this method takes a lot of time and cannot give usable data when the applied voltage is low. An alternative method is to use step-stress tests based on the cumulative life model. This approach can give usable data quickly, but parameter evaluation is much harder than for the constant-stress tests and the approximations necessary for the data solution unavoidably brings errors. In this paper, a new method of estimating the ageing parameter of XLPE is proposed. Step-stress tests are also used but a new parameter evaluation method is presented, which avoids complicated approximations in the data solution. This new method can greatly reduce the errors and easily give the ageing parameter. A series of step-stress tests on 0.3 mm thick XLPE samples have been carried out to illustrate the method. The values of the ageing parameter, *n*, obtained from different methods are compared, and it is found that the new method gives a greater consistency between different test protocols, indicating a more accurate estimation of its value. However, a comparison between the new method and the constant stress accelerated life tests is still needed to confirm the accuracy of the new method.**

I. INTRODUCTION

In recent years, HVDC cables have been greatly improved, 500kV XLPE DC cable has been developed, and many XLPE DC cables of lower applied voltage have been used in HVDC systems [1]. The material is usually designed to withstand the voltage stress for decades of years. In order to obtain the reliability of the design, accelerated life tests are usually taken under constant higher voltage stress based on the empirical model: the inverse power low ($t_L \cdot V^n$ = constant) and the exponential low ($c \cdot \exp(-k \cdot V)$=constant) [2].However, there still is not a unified standard for testing high voltage DC extruded cable systems, only a recommendation. Furthermore the recommendation only gives a lower limit of ageing parameter (n=10 in the inverse power law), which directly determines the voltage used in the test [3]. A more precise value of ageing parameter is needed in order to improve the testing method. The most common method of estimating the ageing parameter uses constant-stress tests at different voltages (electric fields) and is based on the inverse power model, but this method takes a lot of time. Furthermore when the applied DC test voltage is lower than 70% of ramp breakdown voltage the samples are hard to breakdown even after very long voltage duration, thus it is difficult to obtain usable data [4].An alternative approach is to use step-stress tests based on the cumulative life model which is expressed as:

$$L = \sum t_i (V_i)^n + t_{i+1} (V_{i+1})^n \quad (1)$$

$$L = \sum t_i \exp(ku_i) + t_{i+1} \exp(ku_{i+1}) \quad (2)$$

L can be regarded as the cumulative damage or an assessment of ageing after withstanding a series voltage processes (V_i) for some certain times(t_i),and the end-of-life is defined as the time for which L reaches a specified value.

The step-stress tests can reduce test time and ensure quick failure and usable data however the parameter evaluation is much harder than for the constant-stress tests. Several methods have been developed to solve this problem. Wayne Nelson [5] improved the maximum likelihood estimation methods to estimate the data from the step-stress accelerated tests, and Chengjie Xiong [6] developed the maximum likelihood estimation to include the situation where the stress-change times were random. However the maximum likelihood method is still difficult to solve. W. Khachen and J. R. Laghari [2] gave a simple method to estimate the parameters from step-stress tests data. This method treated the total time of applied stress and the voltage as separate Weibull distributions, but this method ignores the step application and brings many errors. Jiqun Chen and Shoutai Wang [7] also used the step-stress method to estimate the ageing parameters. They changed the constant voltage step into a constant ratio (1.06) for the voltage. This helped to solve the complex summation of a series of high order power functions at the expense of ignoring the influence of the last step on which failure occurs. However the last step is the most effective step and it can greatly influence the life parameters of the sample [7].In this paper a new method of estimating the ageing parameter is proposed, based on step-stress tests, which can both reduce the errors and simplify the parameter evaluation.

II. THEORETICAL BACKGROUND

In step-stress tests the voltage is raised in steps and held at a constant voltage for some pre-determined time (dwell time) and then raised again until a voltage is reached at which the

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sample breaks down. The step-test voltage protocol is shown in Fig. 1.

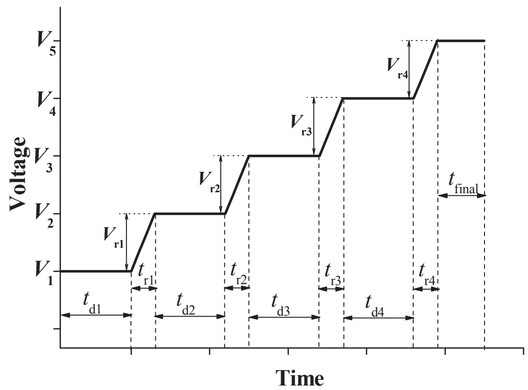


Fig. 1.The voltage protocol for step-stress tests

Here V_i is the withstand voltage for the i-th voltage step, and t_{di} is the dwell time for the i-th voltage step. The survival time for the last voltage step is denoted as t_{final}. The voltage increment between the i-th and (i+1)-th voltage steps is denoted by V_{ri}, and the time taken to increment the voltage by t_{ri}.

Usually the initial voltage V_1, voltage increment V_r, dwell time t_d and the rate of voltage increase k_v, are set to be constant in each set of tests to simplify the analysis. Thus the time for voltage increase t_r is also the same for each step. Several sets of tests with different time intervals are usually held to obtain the ageing parameter by solving the equation set as below:

$$\begin{cases} L = \sum t_{d\text{-}a}(V_i)^n + t_{final}(V_{bd\text{-}a})^n \\ L = \sum t_{d\text{-}b}(V_i)^n + t_{final}(V_{bd\text{-}b})^n \\ L = \sum t_{d\text{-}c}(V_i)^n + t_{final}(V_{bd\text{-}c})^n \end{cases} \quad (3)$$

Here $t_{d\text{-}a}$, $t_{d\text{-}b}$ and $t_{d\text{-}c}$ are the dwell times and $V_{bd\text{-}a}$, $V_{bd\text{-}b}$,$V_{bd\text{-}c}$ the breakdown voltages for test sets a, b and c, with n being the ageing parameter for the samples. L can be regarded as the cumulative damage or an assessment of ageing. It can be seen that even though the equations have been simplified by unifying the parameters, it is still hard to solve them and obtain the ageing parameter without proper approximation, but the greater the approximation the greater the errors it introduces.

In order to decrease the errors, the approximation must be limited as much as possible, and the ageing processes of the lower voltages, the final step, and voltage incremental stage, must be fully considered through the equations shown below:

$$\begin{aligned} L &= t_d \sum (V_i)^n + t_{final}(V_{bd})^n + \int_0^{\frac{V_{bd}-V_1}{k_v}} V(t)^n \, dt \\ &= t_d \sum (V_i)^n + t_{final}(V_{bd})^n + \int_{V_1}^{V_{bd}} V^n d\left(\frac{V-V_1}{k_v}\right) \\ &= t_d \sum (V_i)^n + t_{final}(V_{bd})^n + \frac{1}{k_v} \cdot \frac{V_{bd}^{n+1} - V_1^{n+1}}{n+1} \end{aligned} \quad (4)$$

The first two terms are the same as those in (3) and take account of the contribution to ageing of withstanding the voltage under each step, but now the ageing process of voltage ramp-up is additionally considered and described in the last term.

If three sets of tests a, b and c with different dwell times ($t_{d\text{-}a}$, $t_{d\text{-}b}$, $t_{d\text{-}c}$) have been carried out. For each set of tests, the breakdown time for all the samples usually fit a certain distribution (normal, exponent, Weibull, etc.), a characteristic breakdown time ($T_{bd\text{-}a}$, $T_{bd\text{-}b}$, $T_{bd\text{-}c}$) can be obtained by solve that distribution. As the voltage protocol has been defined, the corresponding breakdown voltage ($V_{bd\text{-}a}$, $V_{bd\text{-}b}$, $V_{bd\text{-}c}$) and the survival time for the last ($t_{final\text{-}a}$, $t_{final\text{-}b}$, $t_{final\text{-}c}$) can be derived from the characteristic breakdown time for each set of tests. Then according to (4), those characteristic values of the three sets of tests form the equation sets below:

$$\begin{cases} L_a = t_{d\text{-}a} \sum (V_i)^n + t_{final\text{-}a}(V_{bd\text{-}a})^n + \frac{1}{k_v} \cdot \frac{V_{bd\text{-}a}^{n+1} - V_1^{n+1}}{n+1} \\ L_b = t_{d\text{-}b} \sum (V_j)^n + t_{final\text{-}b}(V_{bd\text{-}b})^n + \frac{1}{k_v} \cdot \frac{V_{bd\text{-}b}^{n+1} - V_1^{n+1}}{n+1} \\ L_c = t_{d\text{-}c} \sum (V_k)^n + t_{final\text{-}c}(V_{bd\text{-}c})^n + \frac{1}{k_v} \cdot \frac{V_{bd\text{-}c}^{n+1} - V_1^{n+1}}{n+1} \\ L_a = L_b = L_c \end{cases} \quad (5)$$

L_a, L_b, L_c are separately the characteristic cumulative damages for each set of tests. It is still difficult to solve (5) directly, however if a value is assumed for the ageing parameter n they allow the cumulative damages (L_a, L_b, L_c) to be derived easily from (5). Put the assumed n and the cumulative damages (L_a, L_b, L_c) separately into the inverse power law function ($t_L \cdot V^n$ = constant), take logarithms of both sides of the power law function equations so as to turn the power function into a linear function:

$$\begin{cases} \ln(L_a) = \ln(t_a) + n \cdot \ln(V_a) \\ \ln(L_b) = \ln(t_b) + n \cdot \ln(V_b) \\ \ln(L_c) = \ln(t_c) + n \cdot \ln(V_c) \end{cases} \quad (6)$$

Here t_a, t_b, t_c, are life time parameters for the equivalent voltage parameters, V_a, V_b, and V_c for the three different sets, a, b, c. Now the data can be presented as a line in a ln(V)-ln(t) plot as shown below.

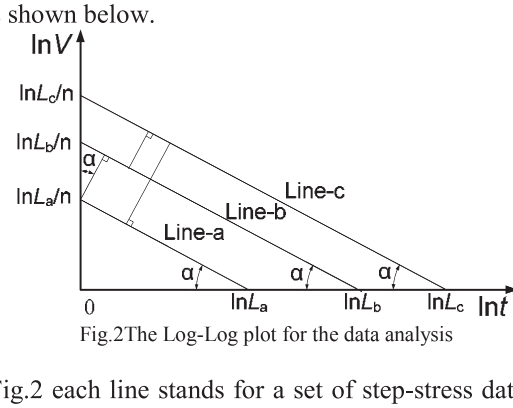


Fig.2The Log-Log plot for the data analysis

In Fig.2 each line stands for a set of step-stress data with a certain dwell time. All the lines are parallel, because the slopes of the lines are only determined by the assumed value of "n". The position of each line is determined by the cumulative damage L.

In an ideal case, L_a, L_b, L_c should be the same when the assumed "n" is the true value of ageing parameter, as the data are from the same material under the same test condition, and the cumulative damage is assumed to be constant for a given material. Thus all the lines should overlap with each other. In a real case the data from the tests are statistically distributed, but it can still be considered that the closer the lines, the closer the assumed "n" is to the true value of ageing parameter. In other words, if an assumed value of "n" can bring all the three lines to the closest approach, then that value of "n" can be regarded as the 'true' ageing parameter appropriate to the material.

The summation and the variance of the perpendicular distances between lines are usually used to describe the degree of discrepancy of the lines. This distance between line-a and line-b d_{ab} can be obtained from (7):

$$d_{ab} = \cos\alpha \cdot \left| \frac{\ln L_b}{n} - \frac{\ln L_a}{n} \right| = \frac{\left| \ln L_b - \ln L_a \right|}{\sqrt{n^2+1}} \tag{7}$$

The summation and the variance of the distances are described by (8) and (9):

$$sum = \sum d_{ij} \tag{8}$$

$$var = \sqrt{\sum d_{ij}^2} \tag{9}$$

Here d_{ij} is the perpendicular distance between the line-i and line-j, *sum* is the summation of the distances, *var* is the variance of the distances. The procedure is thus to select values for "n" covering a reasonable empirical range, with the true value being the one that gives the minimum values for the *sum* and *var* as defined in (8) and (9).

III. Experiments And Results

The test samples are all made of XLPE with a thickness of 0.3mm, and have all been put in a vacuum oven at 353 K for 48 h before the tests so as to eliminate the effect of cross linking byproducts on measurement and to ensure uniform initial thermal and mechanical conditions.

Firstly the breakdown voltages of these XLPE samples at room temperature are obtained by a DC ramp test with the samples under oil. Cylindrical electrodes made of copper (Cu) are used and the ramp rate was 1kV/s. The breakdown voltages fit the Weibull distribution well with a scale parameter (characteristic breakdown voltage) of 96.33kV.

Two kinds of protocols for step-stress accelerated life tests are designed and carried out under DC voltages. The test conditions are the same as the ramp breakdown tests. Protocol 1 is designed for the tests with a constant voltage step (5kV) which means that the voltage increases by add 5kV for each step, protocol 2 is designed with a constant ratio of voltage (1.1) on each step which means that the voltage increment increase by the multiplying factor 1.1 on each step.

Protocol 1: constant voltage step

Three sets of accelerated life tests with different dwell times are carried out, with the dwell times set to be 1 mins, 5 mins, and 25 mins. Six samples are tested for each set of tests. The test conditions are same for each set except for the dwell times: the initial voltage is 50 kV, the voltage step is 5kV, and the rate of voltage ramp-up is 1kV/s. The voltage is raised when the dwell time is completed until the sample breaks down. The breakdown voltage, the number of steps and the survival time on the last step are recorded. The data is given in Table 1.

TABLE 1
TheDataFromTheStep-StressAccelerated Life Tests With Constant Voltage Step

Dwell time (s)	Breakdown voltage (kV)	Steps	Survival time on last step (s)	Total time (s)
1min	80	7	2	392
	80	7	2	392
	95	10	7	592
	95	10	28	613
	100	11	0	650
	115	14	7	852
5min	75	6	234	1759
	80	7	0	1830
	80	7	60	1890
	85	8	26	2161
	90	9	12	2452
	95	10	75	2820
25min	70	5	920	6940
	70	5	980	7000
	70	5	1100	7120
	75	6	710	8235
	80	7	160	9190
	85	8	1300	11835

Protocol 2: constant ratio of voltage

Two sets of accelerated life tests with different dwell times are carried out, with the dwell times set to be 1 mins and 20mins. Six samples are tested for each set of tests. The test conditions are the same for each set of tests except for the dwell times: the initial voltage is 50 kV, the ratio of voltage for each step is 1.1, and the rate of voltage ramp-up is 1kV/s. The voltage is raised when the dwell time is completed until the sample breaks down. The breakdown voltage, the number of steps and the survival time on the last step are recorded. The data are showed in Table 2.

TABLE 2
TheDataFromTheStep-StressAccelerated Life Tests With Constant Ratio Of Voltage

Dwell time (s)	Breakdown voltage (kV)	Steps	Survival time on last step (s)	Total time (s)
1min	88.6	7	25	423.6
	88.6	7	42	440.6
	97.4	8	7	474.4
	97.4	8	22	489.4
	107.5	9	10	547.5
	117.9	10	4	611.9
20min	66.5	4	840	4456.5
	73.2	5	540	5363.2
	80.5	6	480	6510.5
	80.5	6	780	6810.5
	88.6	7	120	7358.6
	88.6	7	180	7418.6

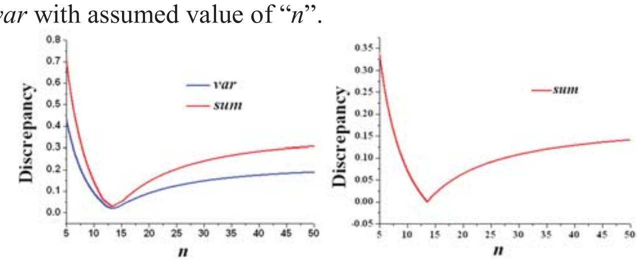
Usually the withstand time for the constant stress test is considered to fit a Weibull distribution, here the total time for the step-stress test is assumed to fit a Weibull distribution. The scale parameter of the Weibull distribution for each set of tests is derived and regarded as the characteristic breakdown time under step-stress accelerated life tests. Through the characteristic breakdown time, the corresponding breakdown voltage, number of steps and the survival time on the last step can be derived. The data is shown in Table 3.

TABLE3

THE CHARACTERISTIC BREAKDOWN PARAMETERS OF THE TESTS

	Constant step			Constant ratio	
	1min	5min	25min	1min	20min
Breakdown time (s)	645	2317	9118.8	527.3	6757.9
Corresponding Breakdown voltage(kV)	95	85	80	97.4	80.5
Steps	10	8	7	8	6
Survival Time on last step (s)	54.7	181.5	88.8	59.9	727.5

After the characteristic parameters listed in Table 3 have been derived, the analytical procedure outlined above and defined in (6) is carried out by determining (5) for the characteristic failure in each set, using a given value of "*n*". Here an empirical range of the ageing parameter from 5 to 50 is assumed, then "*n*" is scanned across the range with an interval of 0.01. The *sum* and *var* are then estimated for the data of protocol 1 with (8) and (9), and the *sum* is also estimated for protocol 2.Fig. 3 shows the variation of *sum* and *var* with assumed value of "*n*".



a. protocol 1 b. protocol 2

Fig. 3 The value of *sum* and *var*

From Fig. 3 it can be seen that no matter whether protocol 1 or 2 is used the values of the *sum* and *var* show the same trend: they firstly decrease with the assumed "*n*", but after reaching a minimum, they increase with "*n*". For the protocol 1, the value of the *sum* is a minimum when the *n* is 13.29, and the *var* takes the minimum value when the *n* is 13.32; for protocol 2, the value of the *sum* is at a minimum when *n* is 13.57.

Since the voltage procedure of protocol 1 is the same as that of [2], and that of protocol 2 is the same as that of [7], the data is also analysed by their methods. The ageing parameters obtained by the different methods are listed in Table 4:

TABLE4

THE AGEING PARAMETERS OBTAINED BY DIFFERENT TESTS AND DIFFERENT METHODS

Protocol 1		Protocol 2	
Reference [2]	New method	Reference [7]	New method
11.8	13.29/13.32	15.7	13.57

It can be seen that the ageing parameters obtained by the new method are quite close to each other, while the ageing parameters obtained by the other two methods have a greater difference. This indicates that the new method can give more consistent results.

As a general statement we can say the ageing parameter obtained from the XLPE samples under DC voltages is in the range 13 -14, so 13.4 can be suggested as a working value for the test design. However, in order to determine the accuracy of the new method, it is intended to carry out a series of comparisons with constant stress accelerated life tests.

IV. CONCLUSIONS

The ageing parameter is the key factor for designing reliability tests for high voltage cables, but it is hard to obtain its value from the traditional constant stress accelerated life tests, while the data from step-stress accelerated life tests is either hard to solve or brings many errors. This paper proposes a new data solution method for estimating the ageing parameter based on step-stress accelerated life tests. The new method fully takes into consideration the voltage protocol including the process of voltage ramp-up. This allows the errors brought by approximation to be avoided as much as possible. Additionally the new method estimates the ageing parameter by a criterion that can avoid a direct complex data solution. Two protocols for step-stress accelerated life tests have been carried out, and it has been shown that the data solutions give very nearly the same values for the ageing parameter indicating that the new method can give more consistent results than the present methods.

These tests suggest that the ageing parameter of the XLPE samples under DC voltage should be taken to lie in the range of 13-14, with 13.4 proposed as a working value for test design.

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