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Title:

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Atlas Transmission Line Breakdown Analysis[♦]

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Abstract

The Atlas facility will use 24 radially converging, vertically oriented and tapered, oil insulated, triplate transmission lines between the Marx generators and the central load region. Among the requirements of the transmission lines are low inductance and high reliability. The inter-conductor gap is nominally 2 cm and the lines taper from a height of 1.75 m at the Marx end to 0.32 m at the output end. The aluminum conductors, held together by 20 insulating spacers, are assembled and inserted as a unit into radial oil-filled steel tanks. The negative, high-voltage, center conductor is 2.54-cm thick and the outer ground conductors are 1.59-cm thick. All 24 triplate-transmission lines connect to a transition section at near 1 m radius that couples the transmission lines to a disk/conical solid-dielectric-insulated power flow channel transmission line terminating at the load. Peak operating voltage on the lines can be as high as 240 kV with an effective stress time of 0.8 μs. Testing of small sections of the total area have been completed and the test results are analyzed to show that the probability of failure at these voltage levels is less than 1 in 1000 system shots.

I. ATLAS MACHINE CONFIGURATION

The Atlas machine [1] has 23 MJ of capacitor bank and is housed in 12 separate Marx tanks surrounding the target chamber. Each tank contains two independent and removable maintenance units composed of a set of four Marx modules. The Marx modules erect at up to 240-kV. The output of each maintenance unit is connected by a set of 56 cables to a load protection switch that also acts as interface between the cables and the transmission line. A total of 24 transmission lines transmit the current to a diameter of 2.3 m where a transition section couples the current to a solid-dielectric insulated, radial transmission line that delivers current to the load.

As seen in Figures 1, the output of each load protection switch is connect to a tapered, vertically oriented, oil insulated, transmission line. The lines, 6.03 m long, are tri-plates whose inter-electrode gaps are nominally 2-cm. The lines taper from a height of 1.75 m at the Marx end to 0.32 m at the output end The aluminum conductors, held together by 20 insulating spacers, are assembled and inserted as a unit into oil-filled steel tanks. The negative, high-voltage, center conductor is 2.54-cm thick and the outer ground conductors are 1.59-cm thick.

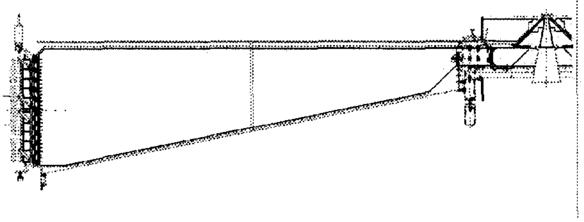

Figure 1. Transmission line drawing shows load protection switch at input and transition region at output of line.

II. TRANSMISSION LINE REQUIREMENTS

Requirements on the transmission lines are more than just transporting 27 – 32 MA from the load protection switch to the transition region. The associated inductance has been minimized to reduce circuit impedance and maximize current amplitude. The configuration described here yields a total of 3.25 nH for the 24 parallel lines. This has been accomplished by using a large tri-plate area and small gap spacing. Finally the area and spacing must be consistent with a breakdown probability that is less than 1 failure per 1000 system shots.

To determine the breakdown probability in the tri-plates requires that we know the field stresses, the surface area associated with that stress level and the effective time for which that stress is experienced. The first step in this process is to establish the circuit. A circuit code, such as Pspice, is then used to determine the peak voltage amplitude and the effective stress time at the various circuit components. Figure 2 shows the circuit used to model the Atlas system. Figures 3 and 4 show the voltage

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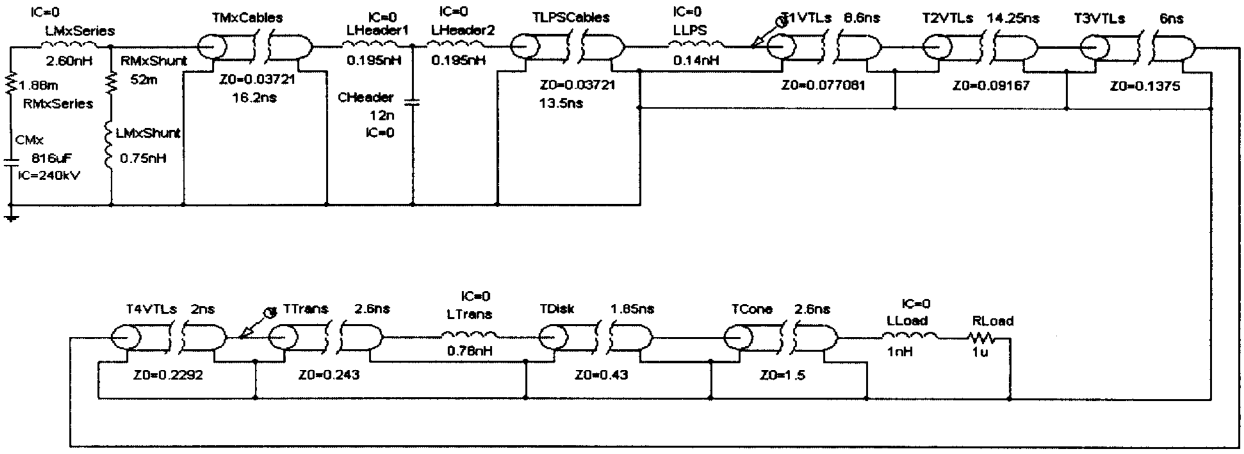

Figure 2. Circuit used to model the Atlas system.

waveform at input to the tri-plates. Voltage amplitude at the transition region, or tri-plate output, is down to 72 % of that at the input. As a result, we conclude that no more than one-half of the total tri-plate area is stressed to within 90 % of the 240 kV input amplitude. For flat surfaces, therefore no enhancements, the probability of breakdown is equally likely to originate on either polarity surface. The total stressed area on each tri-plate is therefore four times the area projected on a plane, or 4 * 6.8 m^2. But only half of this area is stressed to 90 % of peak, so the total stressed area is 24 *13.6 m^2, or 327 m^2. The effective stress time, t_{eff}, is usually defined as that for which the field exceeds 63% of its peak amplitude.

III. BREAKDOWN FIELDS AND PROBABILITY OF FAILURE

Data taken and analyzed at AWE [2] and later at NRL [3] showed that, for uniform field configurations in oil, the field, F_{BD}, for which there is a 50% probability of breakdown could be related to the area under stress and the effective stress time by the expression

$$F_{BD} = 480 t_{eff}^{-1/3} A^{-0.073} \qquad (1)$$

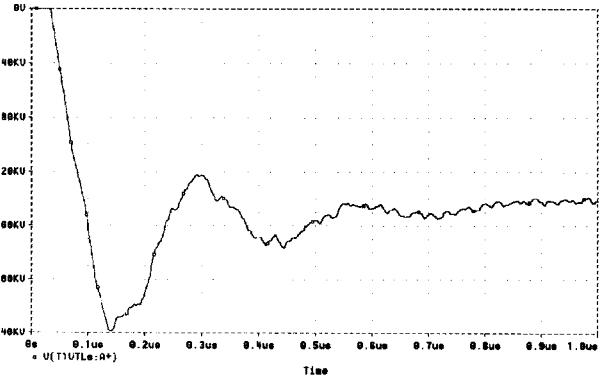

Figure 3. Voltage waveform at input to the tri-plates.

where F_{BD} is in kV/cm, t_{eff} in μs and A in cm^2. For non-uniform fields the F_{BD} in Eq. 1 is replaced by F_{BD}/α where

$$\alpha = 1+0.12\{(E_{max}/E_{mean})-1\}^{1/2}. \qquad (2)$$

The area dependence is important because it relates to the observation that, for a given area, the breakdown field varies from shot to shot and from specimen to specimen. The probability of breakdown is commonly considered to be similar whether testing the same area, A, for N times or for a single test on an area NA. This assumption leads to the conclusion that the probability of breakdown at field E is

$$\text{Probability of failure} = \tfrac{1}{2}(E/F_{BD})^{1/0.073}. \qquad (3)$$

In fact the 0.073 exponent may have two components; one due to shot-to-shot variation and one related to sample-to-sample variation.

Historically t_{eff} was measured on a 1-cos waveform resulting from a Marx charging another capacitor such as a pulse forming line. To find t_{eff} for a waveform that is not 1-cos, one may use the expression

$$t_{eff} = 4/3(\int V^3 dt / V_{peak}^3) \qquad (4)$$

where the factor (4/3) is used to give the historically correct t_{eff} for a 1-cos waveform. From Fig. 3 and 4, the

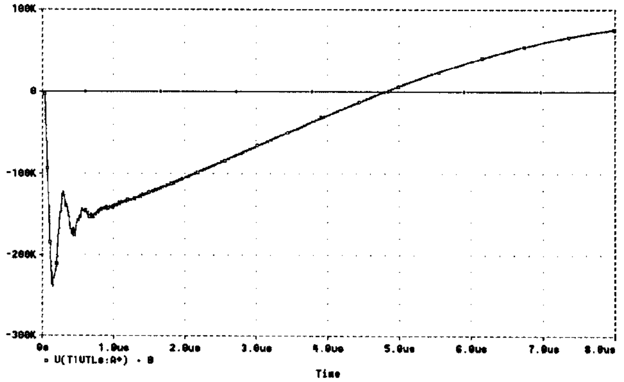

Figure 4. Voltage waveform at input to the tri-plates shows reversal at late time.

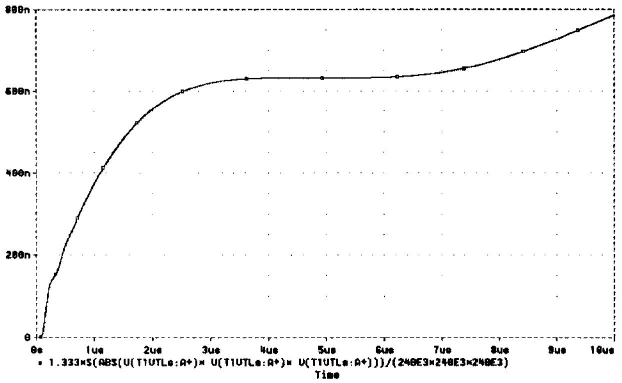

Figure 5. The time history of t_{eff} is closer to 630 ns rather then 400 ns.

time for which the amplitude is greater than 63% of peak is under 400 ns but the integral in Fig. 5, shows t_{eff} to be closer to 630 ns. If late times are included, it is 780 ns. There is no data that we are aware of to suggest how to deal with the voltage reversal and to use the longest t_{eff} appears to be a conservative approach. Data collected at Physics International in the late 1960's suggest that while the 1/3 time dependence is appropriate for t_{eff} in the <300 ns time frame, for long pulses, >2 µs, the exponent may be as small as 1/8. We have used an exponent of 0.151, a value used by Tom Martin of Sandia for a large range of t_{eff}.

IV. SMALL AREA TESTS

At this point the Atlas team concluded that a spacing mean of 2 cm might be appropriate. The peak field in the parallel plate region would be 120 kV/cm for the maximum Marx charge of 240 kV. The predicted breakdown field was near 167 kV:

$$F_{BD} = 480(0.78)^{-0.151}(327*10^4)^{-0.073} = 167 \text{ kV/cm}. \quad (5)$$

The probability of failure was near one in 180 shots:

$$\text{Probability of failure} = ½(120/167)^{1/0.073} = 1/180. \quad (6)$$

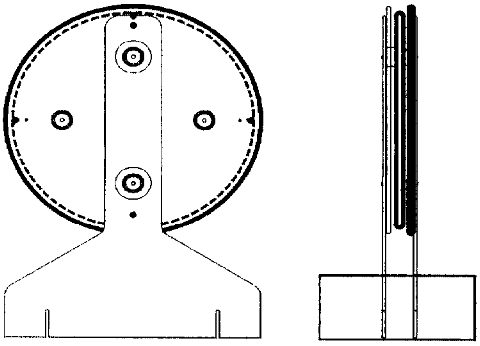

Figure 6. Tri-plate test fixture has 2.63 m^2 of stressed area and 4 insulators.

Table 1. Data from 2.63 m^2 vertical test area and 2 cm gap.

Shot Number	Breakdown	Peak Field F (kV/cm)	t_{eff} (us)	K (kV/cm)
2600	no	250	2.23	>593
2602	yes	263	2.18	622
2603	yes	263	1.37	580
1767	no	230	2.77	>564
1768	yes	248	2.22	588
1769	yes	237	2.24	563
averages		249	2.17	585

A set of 36 inch diameter triplates was fabricated, Fig. 6, to conduct a set of tests determining F_{BD} for this area and also to test the standoff insulators and edge effects. Four insulators were used on this 2.63 m^2 test area and, because the density of insulators and edges per unit area is near double that on the Atlas tri-plates, this is somewhat of an overtest for insulators and edges. Results of the insulator tests are given in another report [4]. Some of the data from the series of test shots is given in Table 1. The analysis in Table 1 suggests that the field at which there is a 50% probability of breakdown is near 20% higher than normally assumed

$$F_{BD} = 585t_{eff}^{-0.151}A^{-0.073} = 480(1.22)t_{eff}^{-0.151}A^{-0.073}. \quad (7)$$

This observation is consistent with earlier reports [5,6] which suggest the vertical plate orientation is advantageous, maybe because debris and air bubbles are less likely to settle on the vertical plate surfaces.

Using Eq. 3 one might suggest that the probability of failure for repeated shots at 410 kV, E=205 kV/cm, with our test apparatus and waveform having t_{eff} near 2.2 µs, will be near 1/30:

$$½(205/249)^{1/.073} = 1/30. \quad (8)$$

However, when firing 111 such shots, only one failure was experienced, shot #2567. This failure occurred after 85 such shots. The oil was stirred to remove carbon from between the surfaces and testing continued to higher voltages.

This failure occurred between the two plate surfaces having 125 finish, used for the last 200 shots. This was the only failure on these surfaces, as all earlier and later failures, including those in Table 1, occurred between surfaces having 32 finish. We conclude that surface finishes 125 or better are adequate and we will use aluminum surfaces with 32 finish for Atlas. Also, we conclude that if the Atlas surfaces are similar to, or better than the test surfaces, that the 1/0.073 in Eq. 3 is pessimistic and a more representative value may be 1/0.05 to determine shot-to-shot performance. However, because of the limited data and because of the desire to be conservative in our predictions regarding Atlas, the 1/0.073 exponent is used in our estimates of Atlas

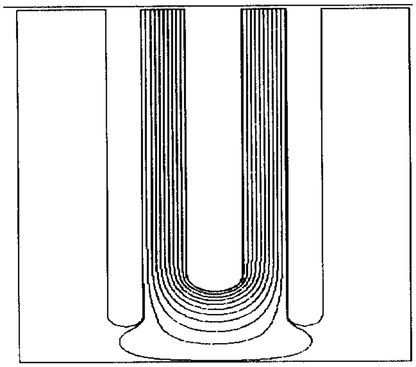

Figure 7. Tri-plate edges have been configured to give reduced E fields on positive plate edges.

breakdown failures. Our estimates may therefore be regarded as reasonable for the first few shots where surface conditions must be demonstrated and sample-to-sample statistics must be included. Later shots may have a lower probability of failure, more representative of the 1/0.05 area dependence.

Fig. 7 shows how the tri-plate edges have been configured both on the test fixture, Fig. 6, and on Atlas to reduce E fields on the positive plates at the expense of enhancing the negative edges. This is generally considered proper because negatively enhanced surfaces, corresponding to impedance greater than 10 Ω, can tolerate fields near 50% higher than in the case of uniform field configurations. Our testing experienced no edge failures. Also, the final insulator configuration, used on all shots in Table 1, failed only on shot 2603 after four earlier failures between the plates. Shot 2603 is included in Table 1 as a failure between the plates only because two insulators failed and one or both tracks may have originated on the uniform field region of the plates. Also, the data from shot 2603 is consistent with other failures in the uniform field.

V. CONCLUSIONS

Table 2 is a summary of the predicted failure probability in the Atlas transmission lines including the transition region near the machine center. Spacings at the transition were reduced to 1.75 cm between the vertical surfaces because of the lower voltages in this region. Predictions in Table 2 are made using the 20% advantage from the vertical tri-plate orientation as observed in our tests and which may be conservative based on references 6 and 7.

Finally, the predictions of Table 2 are based on Atlas operation at 240kV. Instead, Atlas will be operated at closer to 80% of that voltage or 192kV. Rather than introducing a large series resistor to limit capacitor voltage reversal to 15%, Atlas will operate with 44% reversal and reduced voltage with no degradation in current to the load. As a result, the failure rates of Table 2 may be viewed as conservative by a factor near 20, $(.8)^{1/0.073}$.

Table 2. Probability of failure on vertical transmission line surfaces is less than one per one thousand system shots.

Region	Area	t_{eff}	$E^{(1)}$	F_{BD}	Prob. Failures/
	(m^2)	(μs)	(kV/cm)	(kV/cm)	1000 Shots
VTLs:					
Vertical Flats	$327^{(2)}$	0.78	120	$200^{(3)}$	0.5
Horizontal Edges	11.6	0.78	164	$344^{(4)}$	0.02
Transition:					
Vertical Flats	19.6	0.7	100	$208^{(5)}$	0.02
Pos Vertical Edges	0.6	0.7	125	$282^{(6)}$	0.01
Horizontal Neg Edges	3.85	0.7	130	$380^{(7)}$	0

Area, A, is in cm^2

(1) Peak field. (2) Half of total positive and negative surfaces is stressed to 90 % of max E. (3) k = 1.2, because of vertical surfaces and experience suggesting higher F_{BD}. (4) k=1.5, polarity effect because impedance is >10 Ohms, $\alpha = 1.1$. (5) k=1, because surfaces are not large areas but only 25 cm tall. (6) $\alpha = 1.05$. (7) same as (4), $\alpha=1.08$

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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