STUDY OF SIMULATED LIGHTNING DISCHARGE EFFECTS ON WIRES OF A ROTORCRAFT

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ABSTRACT

During a study of the indirect effects of lightning discharges on wires of a rotorcraft performed as part of AFARP 17 (*Anglo French Aeronautical Research Program* Nb 17), it has been necessary to simulate the various parameters of a real lightning stroke (E, dE/dt, I, dI/dt).

In this objective, three different methods have been used: High current pulse injection, low level C.W. current injection and high voltage arc coupling.

In the first part of this paper, we present a short description of the experimental set up and we analyse the data recorded during each experiment.

In the second part, we present the method used in order to determine the participation level of each component of the aggression (I, dI/dt, dE/dt) and we expose why it is very important to take the dE/dt component into consideration.

1 - INTRODUCTION

The simulation of a lightning aggression with all significant physical parameters is technically problematic. It is impossible to reproduce simultaneously the high electric field (E > 500 kV/m, dE/dt > 10^{12} V/m/s) and the high current up to standard (I = 200 kA, dI/dt = $1{,}4.10^{11}$ A/s). To simplify the problem, the accepted custom is that: the magnetic coupling and the hardness of the current waveform give the main effects.

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Concerning wires inside a conductive structure, this rule is perfectly right because the penetration of the electric field is negligible. In the case of a dielectric structure, wires are directly submitted to high electric field and high dE/dt, the rule before is questionable. In the case of interest, our rotorcraft is principaly made in dielectric structure, so we have tried to find the right participation of each component of lightning aggression.

2 - EXPERIMENTAL SET UP

The rotorcraft (A.S. 355 Ecureuil) is made of a conductive (aluminium) sub-structure covered by several dielectric panels (fiberglass).

There are four typical wire routes (see fig. 1).

- Route 1: from equipment case to rotor
- Route 2: --------------------------------- cokpit (upper)
- Route 3: --------------------------------- instrument panel
- Route 4: --------------------------------- tail light

Only the wire L4 is inside a conductive structure, L1, L2, L3 are directly submitted to electric field. All test lines are shielded twisted pairs.

In order to simulate the various threat parameters, two different test configurations have been performed.

For the first configuration (current injection), it was necessary to obtain a good current distribution near the free space distribution. A coaxial return path has been computed and materialized. For the computation, a 2-D wire model code has been used. Field measurements performed in several sections of the structure have qualified the coaxial return path up to 30 MHz. In the objective to obtain normalized waveforms H an D (SAE-AE4L, EUROCAE, see fig. 2), two pulse generators have been used: 100 kV and 600 kV. For the C.W. injection, the structure has been excited by a 100 W amplifier in the frequency range: 1 kHz to 100 MHz.

For the second configuration (high voltage arc coupling), the rotorcraft was put on a platform at 5m above ground, between two flat electrodes (5m X 20m). The helicopter was excited by two arcs, the first arc between the noze and the ground, the second arc between the upper flat electrode and the tail of the rotorcraft. This configuration needed to use a 5 MV Marx generator (see fig. 3).

3 - RESULTS, PROCESSING AND ANALYSIS

a) - First signal processing

Main measurements performed on wires are:

- Shield current
- dE/dt susceptibility
- High impedance common mode voltage

(see fig. 4)

For a first time, the analysis of results consist in the resolution of transfer functions and extrapolation to normalized waveform H and D in order to characterize the electric field effect and the magnetic field effect so as to compare the results obtained by current injection method and by high voltage arc coupling method (see fig. 5)

b) - Results comparison between the high voltage and current injection tests

Frequencies analysis of the various signals show that: the characteristic frequencies of the rotorcraft $\lambda/4$, $\lambda/2$, $3\lambda/4$ are all excited by the high voltage arc coupling test. In the case of the current injection test, it is impossible to excite the $\lambda/2$ characteristic frequency. The difference of wire excitation between the two types of test is given on fig. 6. We can see that in the case of missmatched coaxial structure (short-circuit loaded), the $\lambda/4$ and $3\lambda/4$ frequencies are favourized meanwhile, we would have a tendency to make an additional coupling charge about these frequencies.Concerning the well-matched coaxial structure (Zc loaded), the coupling is reduced because the structure is quasi aperiodic. The good coupling level is obtained in free space by the high voltage arc coupling.

The peak levels of the currents and voltages obtained by extrapolation to normalized waveforms H and D are given on fig. 7a and 7b. Levels of currents and voltages are identical in each test configurations (see fig. 7a for the H wave and fig. 7b for the D wave). However, the maximum peak level on the dE/dt component obtained in most case is about 10^{11} to 10^{12} V/m/s, this value is not realistic because typical inflight values generaly measured are between 10^{12} and 10^{13} V/m/s. [3], [4], [5].

4 - SPECIAL SIGNAL PROCESSING

During the high voltage arc coupling tests, we have performed a particular configuration. The rotorcraft was electricaly floating, it has been charged by a streamer between the flat upper electrode and the structure, one discharge has been provoked between the ground and the noze of the rotorcraft. In this test configuration we have obtained dE/dt component around 10^{13} V/m/s. The measurement of high impedance common mode voltage on the wires L1, L2, L3 has given very important voltage levels, If we compare these values with the same measurements performed in other test configurations (see fig. 8), the perturbation due to higher dE/dt is multiplied by a factor 50 (L1) to 80 (L2). In sight of this important result, it has been necessary to calculate the right participation of each of three main components of lightning aggression (I, dI/dt, dE/dt).

a) - Principle of calculation

The method used to determine the exact participation on electromagnetic wires coupling of each main lightning components consist to use correlation functions.

For two processes X(t) and Y(t) having time limits, the cross-correlation function is given by

$$C_{xy}(\tau) = 1/T \int_0^T X(t).Y(t+\tau).dt \qquad (1)$$

with T = time window

and τ = time shift << T

This function determines the transfer of energy from X(t) to Y(t).

If we proceed this calculus on one process

$$C_{xx}(\tau) = 1/T \int_0^T X(t).X(t+\tau).dt \qquad (2)$$

We will find the self-correlation function, it is representative of the past of the process, it is the "memory process".

The Fourier transform of the function (2) represent the energy spectral density. We will find so the frequency distribution of the energy into the process X(t) (Wiener-Kinchine law).

$$\mathcal{F}[C_{xx}(\tau)] = S(F) = \left| X(F) \right|^{2} \qquad (3)$$

In the same way, the Fourier transform of the function (1) gives the frequency distribution of the energy transfer from X(t) to Y(t).

In the case of interest, we are faced with three input processes I(t), dI(t)/dt, dE(t)/dt and one output process Vs(t): the high impedance common mode voltage. It is easy to determine the "action order" of each process by simple computation of the three cross-correlation functions.

$$C_{IVs}(\Delta t) = \sum_{0}^{n} I(t).Vs(t+\Delta t).\Delta t \qquad (4)$$

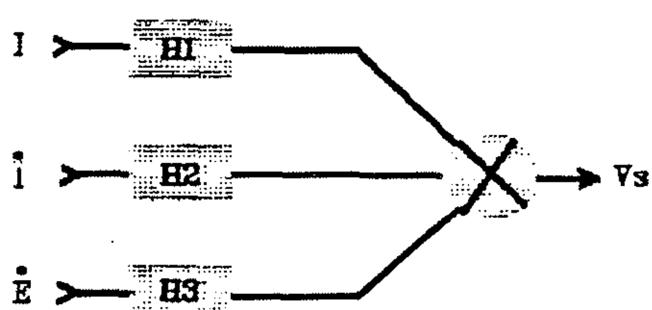
$$C_{IVs}(\Delta t) = \sum_{0}^{n} I(t).Vs(t+\Delta t).\Delta t \qquad (5)$$

$$C_{EVs}(\Delta t) = \sum_{0}^{n} E(t).Vs(t+\Delta t).\Delta t \qquad (6)$$

With - n = number of samples

- Δt = sample interval

Afterwards to have determined the action order of each process, it has seemed interesting to compute the transfer function on the preponderant parameter. We can draw up the block-diagram as follow.



$Vs = I*H1 + \dot{I}*H2 + \dot{E}*H3$

H1,H2,H3 are the three transfer functions.

Afterwards the computation of each self-correlation functions: $C_{II} = C1$, $C_{\dot{I}\dot{I}} = C2$, $C_{\dot{E}\dot{E}} = C3$, $C_{VsVs} = C4$ and the three cross-correlation functions: $C_{IVs} = Cc1$, $C_{\dot{I}Vs} = Cc2$, $C_{\dot{E}Vs} = Cc3$, as well as corresponding spectral densities (S1, S2, S3, S4, Sc1, Sc2, Sc3), we proceed by the following algorithm.

If the action order is, for instance:

- E: 1st order parameter, corresponding transfer function: H3
- I: 2nd order parameter, --: H2
- I: 3rd order parameter, --: H1

To compute:

a) - $\left| H3 \right| = \sqrt{\left| Sc3 \right| / \left| S3 \right|}$ (Estimated function)

b) - $\dot{E}(f) = \mathcal{F}\,[\dot{E}(t)]$

c) - $Vs(f) = \mathcal{F}\,[Vs(t)]$

d) - $Vs\dot{E}(f) = \dot{E}(f) * H3$

e) - $SI,I(f) = Vs(f) - Vs\dot{E}(f)$ (Output signal in the frequency domain for I and dI/dt parameters only)

f) - To compute new cross-correlation functions on two new input parameters

g) - To compute the estimated transfer function H2

h) - To execute the same process from a) to e) in order to obtain the output frequency domain signal SI(f) and to compute the right transfer function H1 by the classical method.

i) - To execute again the complete process so as to obtain the right transfer function H2

j) - At last to execute one more time the complete process in order to obtain the right tansfer function H3 (magnitude and phase).

b) - Results

The computation has been performed on the three wires: L1, L2, L3 for all test configurations, we have recorded that: in all configurations, the preponderant lightning component is the dE/dt. The figures 9 and 10 show the right participation of each component (I, dI/dt, dE/dt) of a lightning aggression. For a dE/dt value of 10^{13} V/m/s, the participation factor for this parameter is 99,2 % (see fig. 9), for dE/dt values from 10^{11} to 10^{12} V/m/s, the participation factor is between 96 % and 98 % (see fig. 10).

The electrical coupling phenomena on high impedance wires has been concealed for a long time because no one type of test until now was able to produce a dE/dt value of 10^{13} V/m/s. The accepted philosophy as yet was that, main effects are magnetics effects so, it is just necessary to determine the transfer functions in comparison with the structure current and to extrapolate up to normalized waveforms; this process can produce serious interpretation errors. The figure 11 shows that the greater perturbation level is obtained on the wires, in the test configuration 8 (dE/dt = 10^{13} V/m/s) included current extrapolations to normalized waveforms H and D.

5 - CONCLUSION

The current injection test configuration take into consideration main effects (magnetic effects) in the case of low impedance loaded lines. The transfer functions obtained by this type of tests are sufficiently significant, the high voltage arc coupling test is giving nothing else.

In the case of an open structure as the rotorcraft "AS 355 ECUREUIL", the principal line routes are practically in free space, these lines are subject to an important electric effect, on high impedance loaded lines the main aggression factor is the dE/dt lightning component, it is giving highest levels what it is possible to obtain by all classical types of test. However, if it is possible to localize with precision the susceptible points of the lines (external parts, no shielding points), it will be necessary to proceed electric fields measurements during a current test injection so as to calculate the corresponding transfer functions and extrapolate to significant level of dE/dt near inflight lightning values. In this hypothesis it will be desirable to elaborate a standard (level and waveform). concerning the dE/dt component.

In all other cases (susceptible points unlocalized), it would be essential to perform local tests so as to recreate punctually the significant dE/dt component of the lightning aggression.

ACKNOWLEDGMENTS

We would like to thank specially R. HOBBS an D.T. JORDAN from ROYAL AEROSPACE ESTABLISHMENT for their great efficciency and precious advices generously given during the C.W. test.

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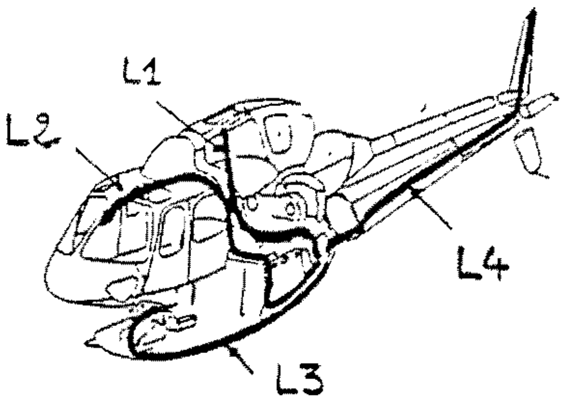


Figure: 1 Wire Routes

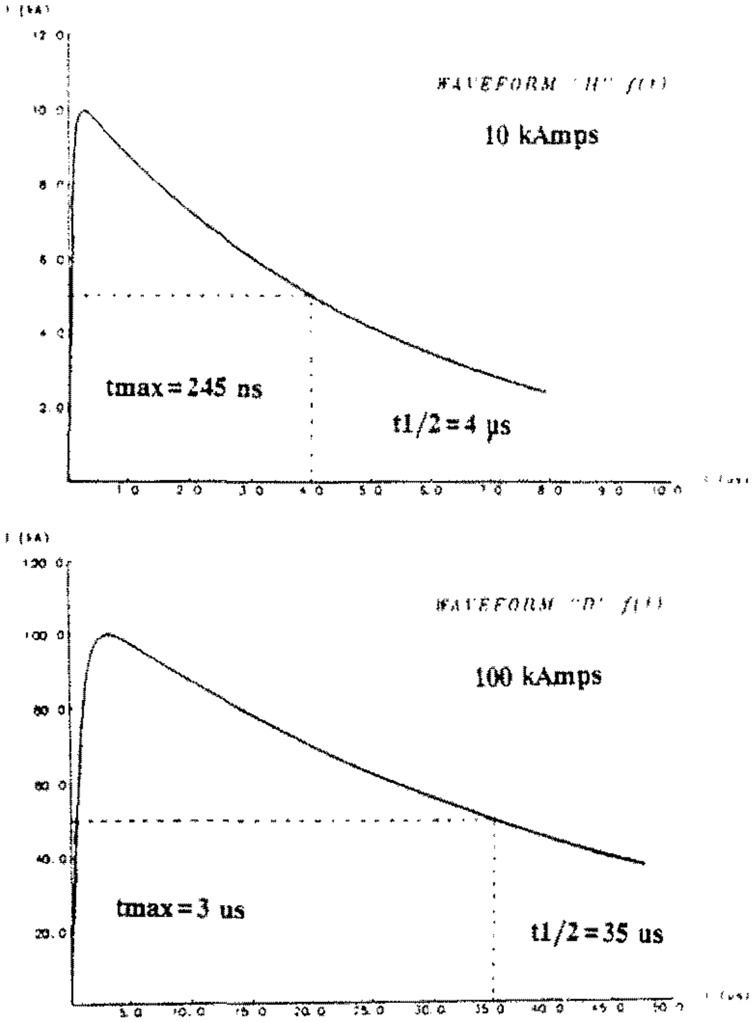


Figure: 2 Normalized current waveforms.

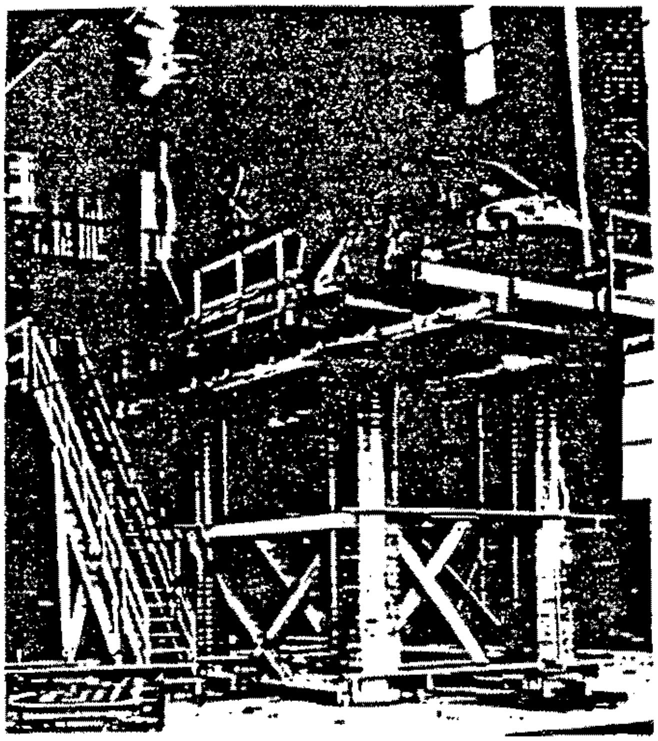


Figure: 3 High Voltage Tests Configuration

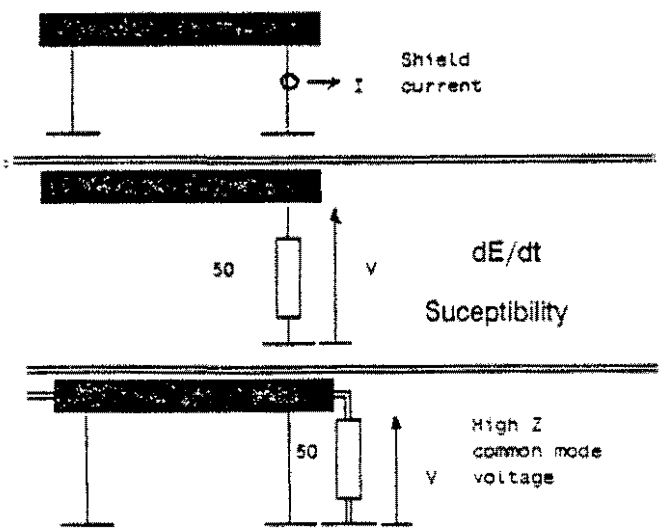


Figure: 4 Wire measurement configurations.

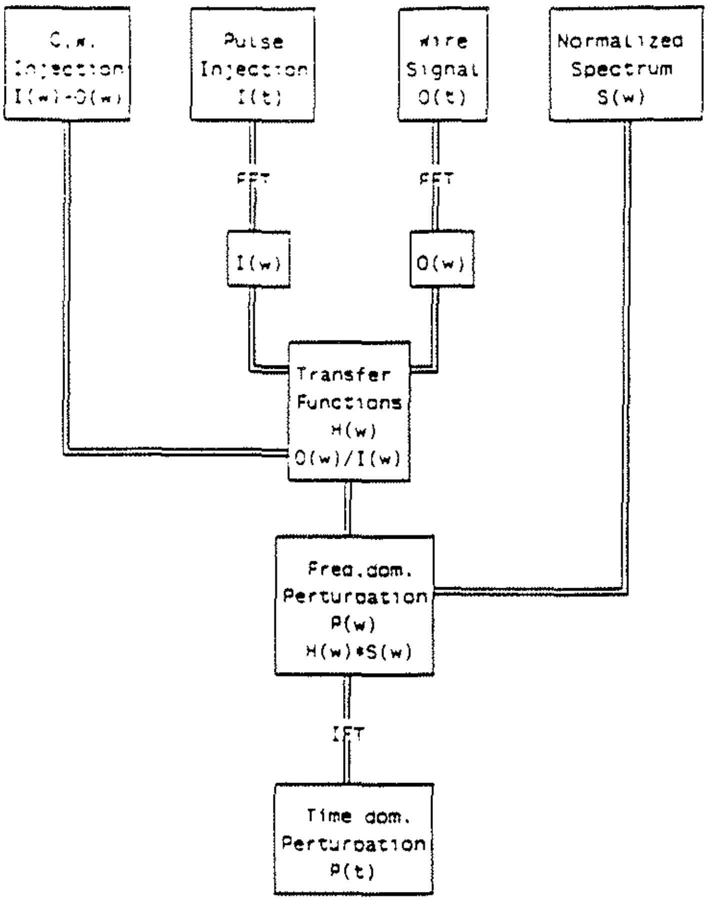


Figure: 5 Signal Processing

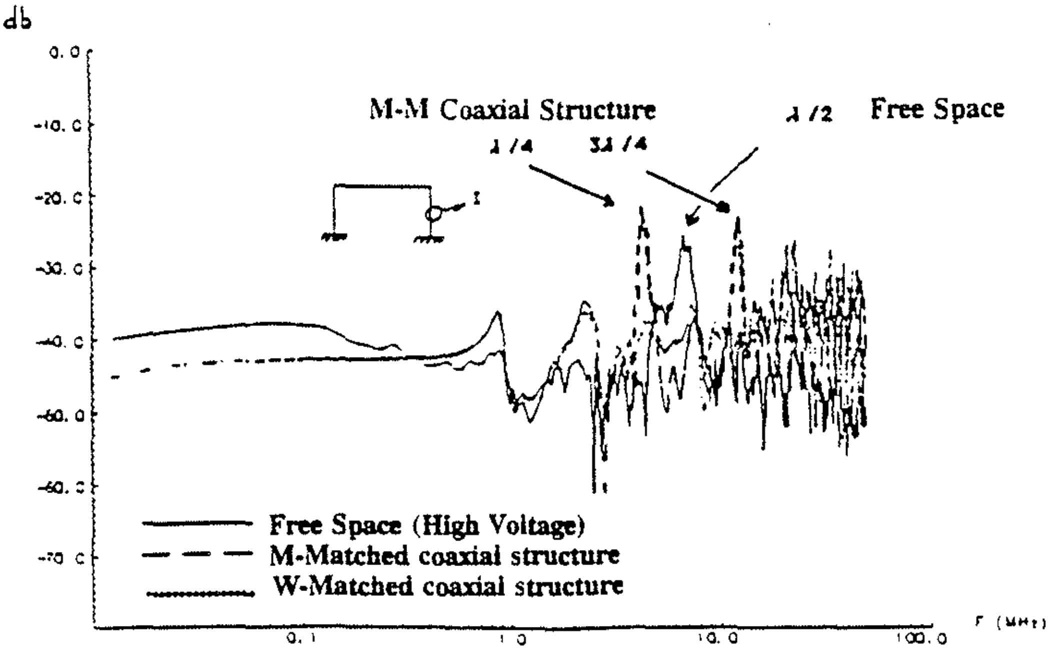


Figure: 6 Line L3. Transfer Function for the 3 Test Configurations

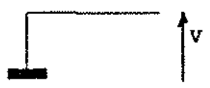
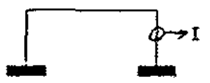
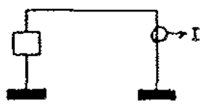
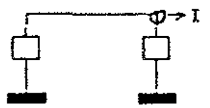
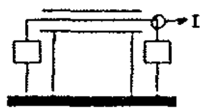
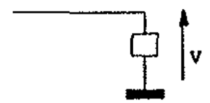
EXTRAPOLATION TO 'D' WAVE				
Line Config.	L1	L2	L3	L4
	3 kV	17 kV	8 kV	1.6 kV
	110 A	1600 A	700 A	40 A
	10 A	150 A	100 A	10 A
	10 A	80 A	50 A	10 A
	100 mA	2 A	1 A	50 mA
				
	4.5 V	12 V	12.5 V	2.5 V

Figure: 7 a

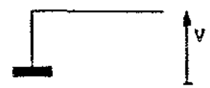
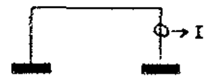
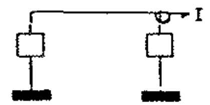
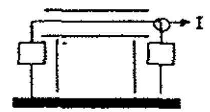
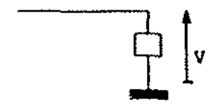
EXTRAPOLATION TO 'H' WAVE				
Line Config.	L1	L2	L3	L4
	4 kV	12 kV	5 kV	1.5 kV
	25 A	150 A	90 A	9 A
	10 A	80 A	40 A	6 A
	10 A	50 A	20 A	5 A
	10 mA	200 mA	150 mA	20 mA
	250 V	500 V	500 V	300 V
	4 V	9 V	9 V	2 V

Figure 7 b

Extrapolation to normalized waveforms H and D

TEST CONFIG.	Line: 1(v)	Line 2(v)	Line 3(v)
1	4.7	3.3	1.
2	0.6	1.	0.25
4	0.5	0.8	0.1
6	0.63	0.8	0.5
7	0.8	1.7	1.5
8*	40.	160.	80.

Figure: 8 Common mode line voltage obtained in all high voltage test configurations.

- 1, 2, 4, 6, 8, : Test configuration & given dE/dt: 10^{11} to 10^{12} V/m/s.
- 8*: Test configuration given dE/dt: 10^{13} V/m/s.

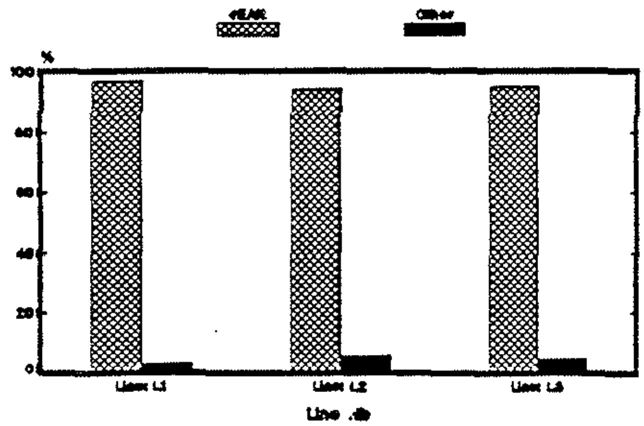


Figure: 9 Energy component part

dE/dt 10^{11} to 10^{12} V/m/s

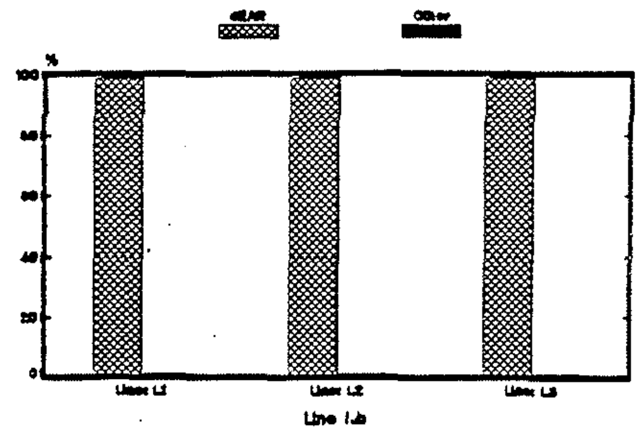


Figure: 10 Energy component part

dE/dt: 10^{13} V/m/s

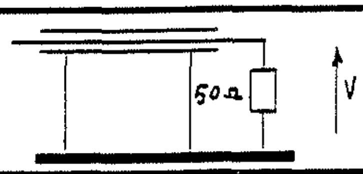
LEVELS COMPARISON			
TEST CONFIGURATIONS			
	L1	L2	L3
CONNECTED	0.63 V	0.80 V	0.42 V
FLOATING	0.80 V	1.80 V	1.80 V
SPECIAL	40. V	160. V	80. V
EXTRAPOL. TO 'H' WAVE	4. V	9. V	9. V
EXTRAPOL. TO 'D' WAVE	4.5 V	12. V	12.5 V

Figure: 11 Common mode line voltage obtained in all test configurations included extrapolation to normalized waveforms H and D.