Confidence Level of High-Altitude Electromagnetic Pulse Field Tests

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Abstract—High-altitude electromagnetic pulse (HEMP) field tests are conducted in the working volume of HEMP simulators to verify the hardness or HEMP survivability of the systems under test. For HEMP field tests, enough confidence should be provided through certain specific test designs. In this paper, the confidence probability of HEMP field tests is defined through a statistical analysis. Based on this definition, the confidence level of the tests is proposed to address the problem that the probability of a failure or significant upset is unknown. The relation between the number of repeated illuminations in one test status and confidence level is provided after analysis. By balancing cost and confidence level, an appropriate number of the repeated illuminations for each test status can be obtained. The comparison with the definition in another article is also made.

1. INTRODUCTION

Electronic components and circuits, such as transistor [1, 2], microcontroller [3], and amplifier circuit [4], are vulnerable under the high-altitude electromagnetic pulse (HEMP) environment. Thus, communication [5], radar [6], and electronic systems [7] can be temporarily upset or permanently damaged by HEMP. Many civil and military systems face the threat of the HEMP environment [8].

Electromagnetic barriers, such as shield [9], surge arrester, and filter, which can be designed to protect the systems from the HEMP environment, are studied by researchers. Critical and sensitive equipment should be enclosed in HEMP barriers. Therefore, it is necessary to test every protection of the systems with a simulated HEMP environment and verify the survivability of the systems. In an HEMP radiated immunity test, the system under test (SUT) that works in its normal working mode is exposed to the HEMP environment. Electromagnetic measurements should be performed during the test. Any condition in the test must be documented and will be used for evaluation.

To obtain the statistical confidence of an HEMP field test, the repeated illuminations in identical test status are implemented. Number of the repeated illuminations has close relation with cost and confidence of the test. The appropriate number should be studied with a statistical method. In [10], the test procedure and characteristics of SUT are analyzed. Based on the analysis, confidence level of HEMP field tests is proposed and discussed. But the authors fail to distinguish one special case of the test data when the probability of a confident HEMP test is discussed. So the confidence level, which is based on the probability of a confident HEMP test, is deviated from the correct value.

In this paper, we focus on confidence level of HEMP field tests from theoretical aspect. HEMP waveform and how an HEMP test should be performed are provided in Section 2. HEMP test procedure and requirements are then briefly introduced in Section 3. In Section 4, confidence level of HEMP field tests is defined and calculated through statistical analysis. From the aspect of result determination of the entire test, all six cases of test results are discussed to calculate confidence probability of the tests. Then further discussion of the confidence level is provided. Finally, the relation of confidence level and number of the repeated illuminations in identical test status are discussed.
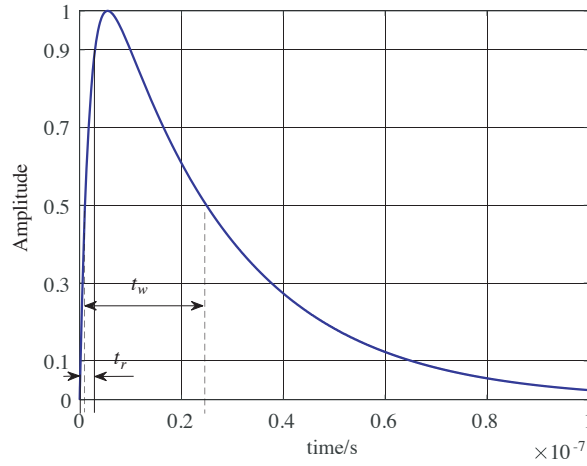
2. HEMP ENVIRONMENT

The radiated HEMP environment created by a high-altitude nuclear burst is composed of three parts [11]: (1) $E1$, the early time: $0 \leq t \leq 1\,\mu s$; (2) $E2$, the intermediate time: $1\,\mu s \leq t \leq 1\,s$; and (3) $E3$, the late time: $t > 1\,s$. Most studies and tests focus on $E1$ HEMP, whose main part is from 100 kHz to 100 MHz in frequency domain. It mainly affects the systems that are not notably large, such as electrical equipment and vehicles. In this paper, we only consider $E1$ HEMP, which we write as HEMP for short in the following paragraphs.

The waveform of HEMP can be expressed in the form of a double exponential pulse as

$$E(t) = K \left(e^{-\alpha t} - e^{-\beta t} \right) \quad (t \geq 0) \tag{1}$$

where t is the time; K is the amplitude factor of the pulse; and α and β are the parameters of the function. $0 < \alpha < \beta$ should be satisfied to maintain a positive wave. The normalized waveform of the double exponential pulse is shown in Fig. 1.

Figure 1. Normalized waveform of HEMP.

In IEC 61000-2-9 [11], the HEMP is defined with the 10–90% rise time of $t_r = 2.5\,ns$ and pulse width at half maximum of $t_w = 23\,ns$. The parameter values are: $\alpha = 4.0 \times 10^7$, $\beta = 6.0 \times 10^8$, and $K = 6.5 \times 10^4$.

In an HEMP field test, the HEMP environment is generated by an HEMP simulator. There is a special volume where the SUT should be placed. During the test, electric and magnetic field measurements are implemented. Some field detectors are placed at predesigned locations to measure the deviation of the electromagnetic environment from the specified HEMP environment. Any condition of the HEMP facilities, instrumentations, and SUT must be documented. Measurements of the coupling currents and voltages on cables and coupling field in shields are defined before the test. All these data are used for evaluation.

3. HEMP TEST PROCEDURE AND REQUIREMENTS

As the confidence of HEMP field tests has close relation with how the test is performed, we briefly consider HEMP field test procedure and requirements in this section. These descriptions also aim to give some general concepts of HEMP field tests. The detailed specifications can be found in standards like IEC 61000-4-25 [12].

3.1. Test Procedure

To provide sufficient confidence, HEMP field tests should follow a series of steps. The procedures of HEMP field tests are briefly summarized as follows.

Before all tests, structure, main function, key elements, and electromagnetic protection of the SUT shall be analyzed. The critical sensitive equipment and shielding methods can then be obtained.

After the pre-test analysis, HEMP tests of the equipment and sub-systems of the SUT, particularly the sensitive ones, are implemented. These tests aim to find the vulnerability of the SUT and reduce the risk. When the SUT satisfies the design requirements, the field test for the entire system can be designed and implemented.

In the system level HEMP field test, the SUT should be placed in the test volume, working at its normal working mode. An HEMP field test commonly contains many test statuses. These statuses can be characterized by the threat level, orientation, polarization, and working mode of the SUT. The polarization is a fixed characteristic of an HEMP simulator. Thus, if it needs to change the polarization, the simulator and test volume will also be changed.

In one test status, there are several repeated illuminations of the simulated HEMP. Number of the repeated illuminations is closely related to confidence of the tests. Before and after every illumination, the system specialists should check the SUT. The state and operating data of the SUT should be documented, especially when there is malfunction or damage.

After all illuminations, the data of the test are sufficient for evaluation. The test is completed.

3.2. Test Requirements

The environment generated by HEMP simulators should satisfy certain requirements, so that the confidence of HEMP field tests can be analyzed.

The waveform of the simulated HEMP field should be confirmed after every illumination. The ranges of the waveform parameters are determined by the actual testing requirement and simulator. The 10–90% rise time is commonly limited in 2.0–3.0 ns, and the pulse width is 18–28 ns. The peak amplitude of the waveform at the location of the SUT should also reach the basic requirement. The tolerance range of the peak amplitude is commonly set as $\pm 10\%$ to $\pm 20\%$.

If there are malfunctions or damage after illumination, the test should be paused until the SUT recovers to the normal working mode. The illumination will be repeated, until sufficient data is obtained.

The sufficient number of the repeated illuminations for the tests is a key problem in the test design. Number of the repeated illuminations correlates with the confidence of the tests. To decide the sufficient number of the repeated illuminations, we will propose and analyze the confidence level of HEMP field tests in the next section.

4. CONFIDENCE LEVEL

In this section, confidence level and number of the repeated illuminations are discussed. In HEMP field tests, we need sufficient data to offer sufficient confidence for the tests and evaluate the vulnerability of SUT. The number of the repeated illuminations per threat level, orientation, working mode and polarization is important but often ignored. In order to determine how many repetitions are required in the tests, confidence probability and confidence level are defined and discussed. From the mathematical viewpoint, confidence probability is defined as the probability that the data of the next additional illumination does not change the original final test result.

In an HEMP field test, the significant malfunction or damage of SUT, which is caused by the HEMP illumination, occurs with probability p_f. Before every illumination, the SUT should return to the normal working mode. Hence, the time interval between two illuminations is sufficiently long to discharge possible coupling voltages and currents. All illuminations can then be treated as independent events. As discussed in [10], if there are k times of malfunction in all N illuminations, its probability is the standard Binomial distribution of probability, as shown in Eq. (2).

$$p_{FA,k} = \left(\begin{array}{c} N \\ k \end{array} \right) p_f^k (1-p_f)^{N-k} \tag{2}$$

In an HEMP test, it is often notably difficult to find the causes of the malfunctions. Whether it is caused by the HEMP environment or the system itself is commonly difficult to determine. Thus, as [10] suggests, at a particular threat level, orientation, working mode and polarization, if the malfunction

occurs no less than 2 times in N illuminations, it is reasonable to believe that the cause is the HEMP environment. Hence, the probability that the SUT fails in the immunity test is

$$p_{\text{fail}} = \sum_{k=2}^{N} p_{FA,k} = \sum_{k=2}^{N} \binom{N}{k} p_f^k (1-p_f)^{N-k} = 1 - \sum_{k=0}^{1} \binom{N}{k} p_f^k (1-p_f)^{N-k}$$

$$= 1 - [1 + (N-1)p_f](1-p_f)^{N-1} \tag{3}$$

As shown in Eq. (3), the fail probability of the test is correlated to malfunction probability and number of the repeated illuminations in the identical test status. Fig. 2 shows the curves of p_{fail} with different p_f and different N in a given test status.

The curves in Fig. 2 illustrate that the probability p_{fail} increases with the increase of malfunction probability and number of the repeated illuminations. In order to get the same fail probability in the test to discover the vulnerability, the SUT with lower p_f needs more illuminations. For example, if the malfunction probability is $p_f = 0.4$ and the number of the repeated illuminations is $N = 3$, the probability that the SUT will fail in the test is 35%. If we only change the number of the repeated illuminations to 5 and 7, the probability p_{fail} can reach 66% and 84% separately.

To inspect whether the number of the repeated illuminations can provide sufficient confidence for the HEMP field test, we should focus on the test results of the N and $N+1$ illuminations. If the test result is changed after the $(N+1)$th illumination, it means the $(N+1)$th illumination is very necessary. We can then determine that the number of the repeated illuminations N is insufficient for the confidence of the HEMP field test. Thus, the test with the N illuminations is not a confident test.

Table 1 lists all the possible results of the $N+1$ illuminations. It is apparent that sum of the probability of the six cases is 1. From Table 1, it is easy to distinguish all the cases of a confident test.

Among the six cases, cases 1, 2, 3, 5, and 6 are confident tests. Only in case 4 the test result is changed after the $(N+1)$th illumination. So the probability that the data of the $(N+1)$th illumination changes the result of the previous N illuminations is
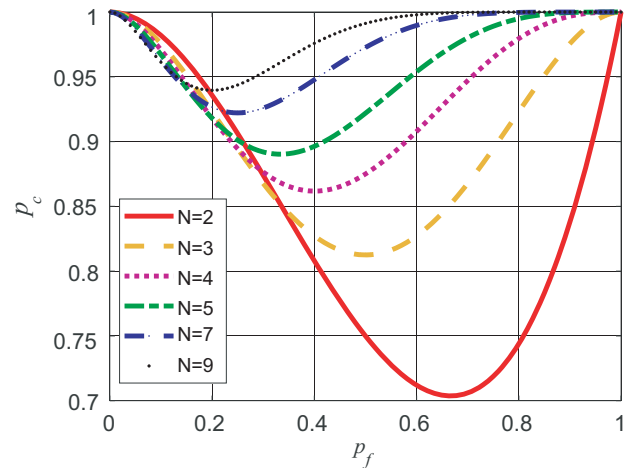
$$p_{\text{changed}} = N \cdot p_f (1-p_f)^{N-1} \cdot p_f = N \cdot p_f^2 (1-p_f)^{N-1} \tag{4}$$

As shown in Eq. (5), confident probability of the HEMP field test can be defined as the sum of the probability of cases 1, 2, 3, 5, and 6. It is the probability of a confident HEMP test.

$$p_c = p_{\text{fail}} \cdot 1 + N \cdot p_f (1-p_f)^{N-1} \cdot (1-p_f) + (1-p_f)^N \cdot 1$$

$$= 1 - \sum_{k=0}^{1} \binom{N}{k} p_f^k (1-p_f)^{N-k} + (1 + N \cdot p_f) \cdot (1-p_f)^N \tag{5}$$
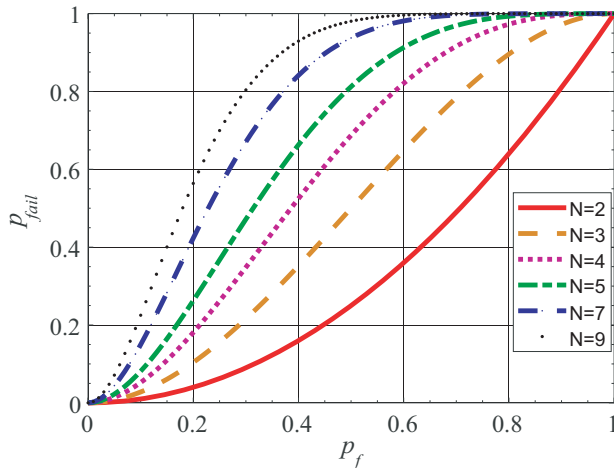
Figure 2. Probability p_{fail} that the test fails.

Figure 3. Confidence probability of an HEMP field test.

Table 1. Six different cases of the test result.

Case	The number of malfunctions in previous N illuminations	The test result of the previous N illuminations	The data of the $(N+1)$th illumination	The test result of the $N+1$ illuminations
1	0	Pass	Normal	Pass
2				Malfunction	
3	1	Pass	Normal	Pass
4				Malfunction	**Fail**
5	≥ 2	Fail	Normal	Fail
6				Malfunction	

Equation (5) can be rewritten as

$$p_c = 1 - p_{\text{changed}} = 1 - N p_f^2 \cdot (1 - p_f)^{N-1} \tag{6}$$

As shown in Eq. (6), confidence probability of the HEMP field test is the probability that the data of the $(N+1)$th illumination does not change the result of the previous N illuminations. Fig. 3 shows the confidence probability of the HEMP field test with different number of the repeated illuminations. If the malfunction probability p_f converges to 0 or 1, p_c tends to 1. Thus, in this situation, the result of the $N+1$ illuminations tends to be identical to the result of the N illuminations. In the middle part of the curves, probability p_c reaches its minimum. As an example, the minimal confidence probability of the HEMP test with $N = 2$ repetitions is 70.4%. If the number of the repeated illuminations increases to 3, 5 and 7, the minimal confidence probability is 81.3%, 89.0% and 92.2%.

In actual HEMP field tests, the malfunction probability p_f of SUT is commonly unknown and difficult to attain. Thus, the minimal confidence probability plays an important part in determining the number of the repeated illuminations. It can be defined in terms of confidence level as

$$p_{CL} = \min_{p_f}(p_c) \tag{7}$$

Figure 4 shows p_{CL} with different numbers of the repeated illuminations. The range of N is 2–30. As shown in Fig. 4, the minimum value is 70.4% with $N = 2$. p_{CL} continues increasing when N increases, but the growth rate decreases. And p_{CL} rapidly increases from $N = 2$ to 10.

Table 2 lists the confidence level with the number of the repeated illuminations of 2–10 with intervals of $\Delta N = 1$ and 10–50 with intervals of $\Delta N = 10$. The confidence level increases to 90.9% when the number of the repeated illuminations is $N = 6$. As an extreme condition, the confidence level increases to 99.9% when the number of the repeated illuminations is $N = 50$.

Table 2. Confidence level with the number of the repeated illuminations from 2 to 50.

N	2	3	4	5	6	7	8	9	10	20	30	40	50
p_{cl}	70.4%	81.3%	86.2%	89.0%	90.9%	92.2%	93.2%	94.0%	94.6%	97.3%	98.2%	98.7%	99.9%

To inspect the increasing rate of p_{CL}, Δp_{CL} is set as

$$\Delta p_{CL}(N) = p_{CL}(N + 1) - p_{CL}(N) \tag{8}$$

As shown in Fig. 5, Δp_{CL} continues decreasing when N increases. If there is $N \geq 5$, Δp_{CL} will be less than 2%.

The values of Δp_{CL} are listed in Table 3. With the number of the repeated illuminations increases to 7, Δp_{CL} decreases to 1.0%. In this case, it is not economical to increase the confidence level by increasing the number of the repeated illuminations.

Table 3. Increasing rate of the confidence level with the number of the repeated illuminations from 2 to 10.

N	2	3	4	5	6	7	8	9	10
Δp_{cl}	10.9%	4.9%	2.9%	1.9%	1.3%	1.0%	0.8%	0.6%	0.5%
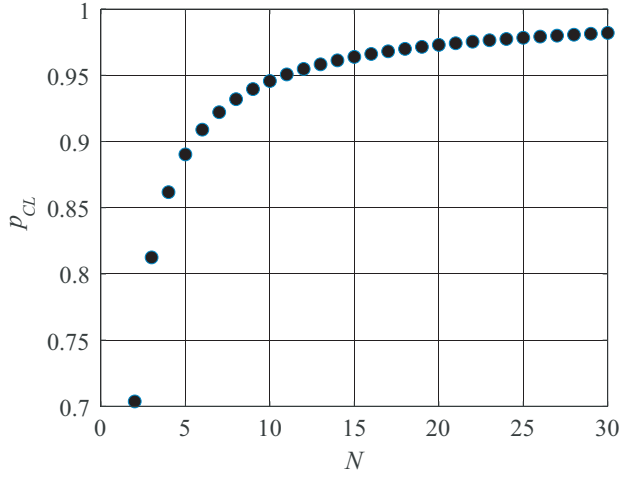
Figure 4. Confidence level of an HEMP field test as a function of the number of the repeated illuminations.
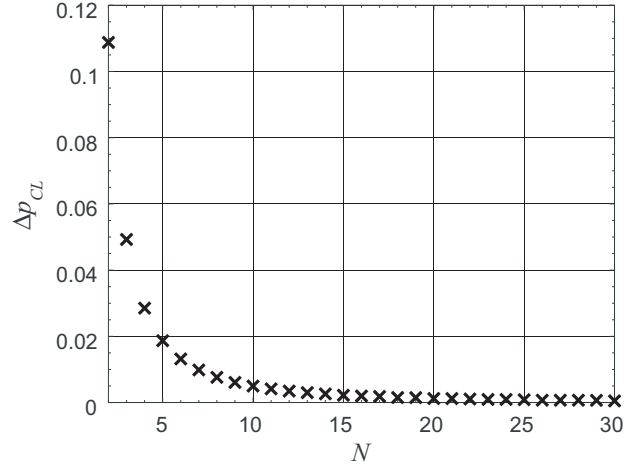
Figure 5. Increasing rate Δp_{CL} of the confidence level.

In actual use, the cost of HEMP field tests should also be considered. The proper number of the repeated illuminations in one test status should be selected with a consideration of both p_{CL} and cost. From the above analysis, the number of the repeated illuminations should be selected in the region of $[3, 7]$. In this region, the confidence level is 81.3–92.2%, which is commonly sufficient for use. If there are more than 7 repetitions, Δp_{cl} is less than 1.0%. In this situation, although the confidence level increases, the performance-price ratio decreases.

Compared to [10], all the differences are derived from the definition of the confidence probability. In [10], it is defined as

$$p_c = (1 - p_f)(1 - p_{\text{fail}}) + p_{\text{fail}} \tag{9}$$

As we can see from Table 1, $(1 - p_f)(1 - p_{\text{fail}})$ is the probability of cases 1 and 3. p_{fail} is the probability of cases 5 and 6. So p_c in [10] is the sum of the probability of cases 1, 3, 5, and 6 in Table 1.

Compared to the definition in this paper, case 2 is not included. But from Table 1 and the concept of a confident HEMP field test, it is obvious that case 2 is also a confident HEMP field test. In case 2, although the SUT fails in the $(N + 1)$th illumination, the test result of the SUT still passes. It is the

Table 4. (a) Confidence level with the number of the repeated illuminations from 2 to 10. (b) Increasing rate of the confidence level with the number of the repeated illuminations from 2 to 10.

(a)

N	2	3	4	5	6	7	8	9	10
p_{cl}	61.5%	74.0%	80.3%	84.1%	86.6%	88.5%	89.9%	91.0%	91.2%

(b)

N	2	3	4	5	6	7	8	9	10
Δp_{cl}	12.5%	6.3%	3.8%	2.6%	1.9%	1.4%	1.1%	0.9%	0.7%

same as the result of the N illuminations. This is based on the criteria of the determination of failure, as shown in the third paragraph of Section 4. It is the same in the two papers. From this point of view, case 2 is still a confident HEMP field test. The probability of case 2 should be added to the confident probability of the HEMP field test.

Thus, the confidence probability proposed in [10] is lower than the correct value. For verification, the confidence level and its increasing rate with the number of the repeated illuminations from 2 to 10 in [10] are shown in Tables 4(a) and (b), respectively.

5. CONCLUSION

This paper mainly discusses the confidence level of HEMP field tests. The confidence probability and confidence level of HEMP field tests are defined and analyzed. Based on the definition and analysis, the relation between the suitable number of the repeated illuminations in one particular test status and the confidence level is studied and provided. It is indicated that the confidence level continues to increase along with the increase of number of the repeated illuminations. But the increasing rate rapidly decreases. The suggested region of the number of the repeated illuminations is then proposed. Finally, the definition in another article is discussed. The neglect of one possible condition of the paper is analyzed. This work can be used to guide the design of an HEMP field test in choosing the number of repeated illuminations.

Whether this research could be used in HEMP pulsed current injection (PCI) tests needs further study, as HEMP PCI test is more targeted to SUT. The determination of the failure of SUT should be rediscussed in HEMP PCI test.

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