Sensor and Simulation Notes

Note 573

25 December 2015

Risetime Evolution in HEMP (High-Altitude Electromagnetic Pulse) E1Waveforms - Technology and Standards

D. V. Giri
Pro-Tech, 11-C Orchard Court, Alamo, CA 94507
Department of ECE, University of New Mexico, Albuquerque, NM

and

William D. Prather
Air Force Research Laboratory, Kirtland AFB, NM 87117

Abstract—There are many different definitions of the risetime of a transient waveform. In the context of HEMP standards, the 10-90% risetime of an idealized double exponential waveform has been defined and used for many decades. However, such a risetime definition is not strictly applicable to the transient voltage out of a pulse generator, since no practical switch can close in zero time. In this paper, we discuss various definitions and their applicability. More importantly, pulse power technology has evolved over 5 decades and the achievable risetimes have come down from 10's of ns to 10's of ps. As a corollary, the highest achievable voltage gradient has been going upwards of 10^{15} V/s. In this paper, we review the definitions of risetime, and trace the evolution of technology and HEMP Standards, exclusively for the E1 environments.

This note is an adaptation of a paper published by the authors in IEEE Transactions on Electromagnetic Compatibility, Volume 55, Issue 3, June 2013, pp 484-491.

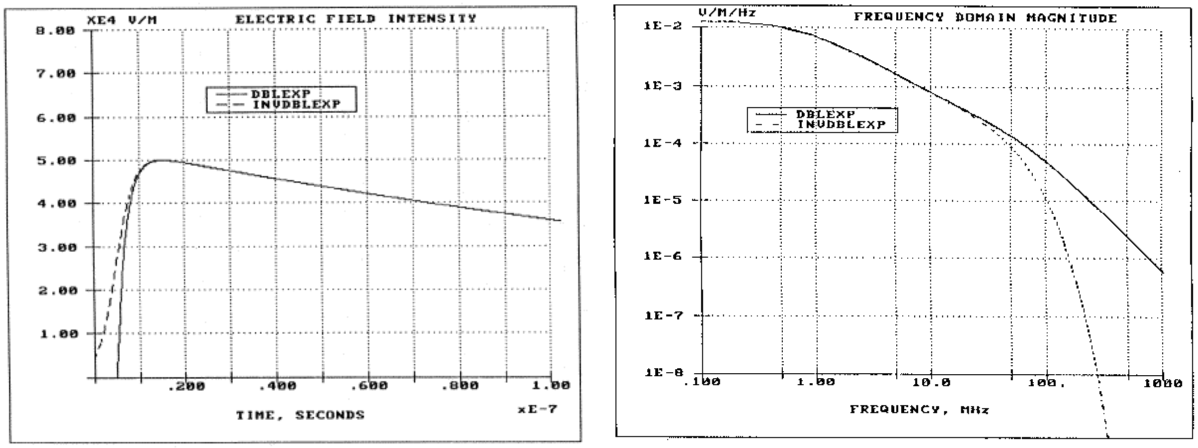
I. INTRODUCTION

A transient pulse generator is at the heart of any HEMP or hyperband system [1] providing the required hyperband energy. Another paper [2] in this special issue discusses three basic types of HEMP simulators namely, (a) guided wave, (b) radiating and (c) hybrid type that combines features of both guided wave and radiating types. In all of these HEMP simulators the simulated electromagnetic environment, $\vec{E}(\vec{r},t)$ *and* $\vec{H}(\vec{r},t)$ have some special relationship with the applied voltage waveform, *V(t).* Consequently, the temporal and spectral purity of the voltage waveform governs the quality of the simulation. The voltage waveform has a certain bandwidth and the simulator is generally expected to have a larger bandwidth to faithfully propagate all of the frequencies contained in the voltage waveform. The transient pulse generator is best viewed as part of a wave launching system. It is simplistic to think of the pulse generator as merely a high-voltage device. It connects to a guiding wave structure or an antenna, and this interface between the pulse generator and the simulator has to be a "high-frequency" connection to ensure no degradation of risetime. Therein lies the conflict. High-voltages require larger stand-off distances and high-frequencies require shorter distances, to minimize unwanted inductances and stray capacitances. Large structures will then require trade-offs and engineering compromises. Our objective in this paper is to initially review HEMP Standards in Section II and also point out how to translate the standards into specifications. In Section III, we look at risetime definitions and trace the evolution of switching technology that has permitted increasing voltages to be switched in shorter times. The paper is concluded with some summarizing comments in Section IV followed by a list of references.

II. UNCLASSIFIED HEMP STANDARDS

Unclassified HEMP standards are characterized by idealized double exponential (DEXP) and quotient exponential (QEXP) waveforms. The HEMP standards are derived by enveloping (in time and frequency domains) many possible waveforms. Then, a mathematical model is created that best expresses both the temporal as well as the spectral characteristics of the envelope. The measured time-domain waveforms from a high altitude detonation are not perfect double exponentials. The waveforms vary quite a bit depending on weapon design, altitude, etc. The double exponential is a model, and a mathematical representation of an envelope.

The model is chosen as a convenient analytic expression whose frequency spectrum envelopes that of the actual HEMP from the weapon. It is analytic and convenient to use. It is a reasonable representation of the HEMP, and its time-domain properties (risetime and exponential decay) are used to design high voltage generators that are used for testing. This is illustrated in Fig.1 for the double exponential (DEXP) and Quotient exponential (QEXP) models.



(a)Temporal waveform

(b) Spectral magnitude

Fig. 1.Time and frequency domain waveforms for HEMP comparing the double exponential and the quotient exponential models

A. *Double Exponential Representation*

The double exponential description of the HEMP waveform has been used since the early days of HEMP research and well described in [3]. The time domain expression is,

$$
\begin{aligned}
&E(t) = E_o\,[\,e^{-\alpha(t-t_o)} - e^{-\beta(t-t_o)}]\,u(t-t_o) \;\; V/m \\
&E_o = \text{ field intensity constant } \;\; V/m \\
&\alpha = \text{ decay constant } \qquad \text{rad/s} \\
&\beta = \text{ risetime constant } \qquad \text{rad/s} \\
&u(t\text{-}t_o) = \text{unit step function} \\
&t_o = \text{ time shift } \quad s \qquad\qquad (1)
\end{aligned}
$$

and the frequency domain expression is

$$
\begin{aligned}
&\tilde{E}(\omega) = E_o\left(\frac{1}{j\omega+\alpha} - \frac{1}{j\omega+\beta}\right) \\
&\tilde{E}(\omega) = \textit{Fourier transform of } E(t) \quad \frac{V}{m-Hz} \\
&\omega = 2\pi f = \textit{radian frequency} \quad \textit{radians/s} \\
&j = \sqrt{-1} \qquad\qquad (2)
\end{aligned}
$$

The double exponential may be characterized in a number of ways. The equations are defined by the three variables, E_o, α, and β, which precisely define the double exponential waveform. The time domain representation, however, is typically characterized by quantities more easily related to the measured waveform. That is, (a) Peak electric field, E_p (Note: $E_p \neq E_o$), (b) 10-90% risetime, t_r, (c) Full-width, half max(FWHM) or the e-fold decay time, the time when the amplitude reaches 1/e of E_p (≈ 37 %). These are chosen because they can be read right off the measured curves.

In 1975, Bell Laboratories published an EMP engineering handbook [4] which used this expression to describe the HEMP waveform. The parameters that were used in the handbook were E_o = 52.5 kV/m, $\alpha = 4.0 \times 10^6$radians/sec and $\beta = 4.76 \times 10^8$radians/sec, which means that E_p = 50kV/m, $t_r = 2.2/\beta$ = 5.5ns, the low frequency spectral density = 14.4 [mV/(m-Hz)], the first break frequency occurs at $\alpha/(2\pi)$ = 637 kHz, and the second break frequency occurs at $\beta/(2\pi)$ = 76 MHz. It is noted that the Bell Standard [4] has the widest waveform with the highest peak amplitude. In reality, these do not occur together. The electric field amplitude is not high when the pulse is wide. More recent standards address this issue by considering the area under the temporal electric field which is related to the low-frequency content in estimating the pulse width.

The only drawback of the DEXP form is that it is discontinuous at t = 0, which creates a discontinuity in the first time derivative. This is not consistent with natural physical processes and creates computational difficulties. However, the simple analytic DEXP waveform has been used for many years to approximate important characteristics of HEMP waveforms and simulators, but it does have this limitation. As a result, another analytical form was derived.

B. *Inverse Double Exponential or Quotient Double Exponential (QEXP)*

In order to correct for the discontinuity, another analytic form was derived, which is the reciprocal of sum of two exponentials, sometimes referred to as inverse or quotient double exponential [2] as shown in Equations 3 and 4. The time domain form is

$$E(t) = \frac{E_o}{[e^{\beta(t-t_o)} + e^{-\alpha(t-t_o)}]} \quad V/m \qquad (3)$$

and the frequency domain form is

$$\tilde{E}(\omega) = \frac{E_o\,\pi}{(\alpha+\beta)}\ \csc\left[\frac{\pi}{(\alpha+\beta)}(j\omega+\beta)\right] e^{-j\omega t_o} \quad \frac{V}{m-Hz} \quad (4)$$

This waveform has the advantage that it has continuous time derivatives of all orders for all times. The disadvantage of this expression is that it extends to t = - ∞ and has infinite number of poles in the frequency domain.

The parameter t_0 is used to adjust the amplitude of the signal for arbitrarily small values of t <0. We can now turn our attention to unclassified HEMP standards. There are at least 7 unclassified HEMP specifications that are either DEXP or QEXP waveforms. Arranged chronologically, these are listed in Table 1. The various parameters of the above unclassified HEMP Standards are compiled and listed in Table 1. A comparison plot is shown in Fig. 2.

	Bell Labs (1960s)	**Baum (1992)**		**IEC-77C (1993)**	**Leuthäuser (1994)**	**VG95371-10 (1995)**	**IEC 61000-2-9 (1996)**
Parameter	**DEXP**	**DEXP**	**QEXP**	**DEXP**	**QEXP**	**DEXP**	**DEXP**
Reference	[4]	[5]		[6]	[7]	[8]	[9]
$t_{10\%-90\%}$	4.6 ns	2.5 ns	2.4 ns	2.5 ns	1.9 ns	0.9 ns	2.5 ns
Peak Field E_0	50 kV/m	50 kV/m	50 kV/m	50 kV/m	60 kV/m	65 kV/m	50 kV/m
FWHM	184 ns	~23 ns	~24 ns	23 ns	23.8 ns	24.1 ns	23 ns
constant	1.05	1.3	1.114	1.3	1.08	1.085	1.3
α (1/sec)	$4\text{x}10^6$	$4\text{x}10^7$	$1.6\text{x}10^9$	$4\text{x}10^7$	$2.20\text{x}10^9$	$3.22\text{x}10^7$	$4\text{x}10^7$
β (1/sec)	$4.76\text{x}10^8$	$6\text{x}10^8$	$3.7\text{x}10^7$	$6\text{x}10^8$	$3.24\text{x}10^7$	$2.07\text{x}10^9$	$6\text{x}10^8$
Energy Density (J/m^2)	0.891	0.114	0.107	0.114	0.167	0.196	0.114

Table 1.Parameters of Unclassified HEMP Standards (NOTE: IEC 77C [6] is same as DEXP in Baum [5])

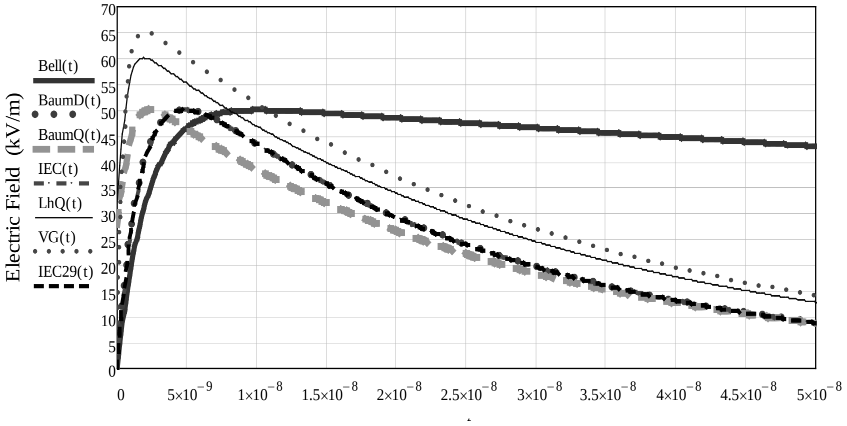


Fig. 2.Time Domain Plots of the unclassified civilian HEMP standards in Table 1.

In addition to the civilian HEMP standards described above, there is also a military standard [10], MIL-STD-464, which is identical to the HEMP standard in IEC 61000-2-9. For completeness, the MIL-STD-464-A HEMP waveform is shown in Fig. 3. It should be noted that we are only dealing with unclassified E1 HEMP standards in this paper.

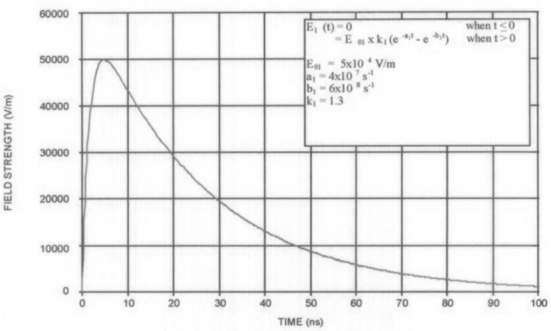


Fig. 3.E1 HEMP Environment form MIL-STD-464-A [10], which is identical to IEC 61000-2-9.

In summarizing the unclassified civilian and military HEMP standards, one might say that these standards are characterized in time domain by three numbers: peak field, 10%-90% risetime, and the full width half maximum (FWHM). The ranges of the three parameters in the eight unclassified standards that we have reviewed above are as follows:

i) Peak electric field ranges from 50 to 65 kV/m
ii) 10%-90% risetime ranges from 0.9 ns to 4.6 ns
iii) FWHM ranges from 23 ns to 184 ns.

It is observed that over the last 40 years, the risetime and duration of the HEMP in unclassified standards has come down by factors of 5 and 8 respectively!

The earliest HEMP Standard [4] used the slowest and the widest pulse calculated at that time. As we learned later, this led to over-testing of low frequencies and under-testing at higher frequencies.

Returning to our discussion of the rise time, the conventional definitions are the exponential rise and the 10-90% rise related for idealized DEXP waveform, by

$$\text{exponential risetime} \equiv t_e = \frac{t_{10\%-90\%}}{\ell n(9)}$$

$$\cong \frac{t_{10\%-90\%}}{2.197} \cong 0.455\ t_{10\%-90\%} \qquad (5)$$

In the previous expression, ℓn (9) in the above expression is the natural logarithm of 9. In practical terms, pulse generators that aim to simulate the HEMP standards cannot be ideal exponentials. For this reason, a better definition of risetime [3, 11] has been offered as follows:

$$\text{maximum rate of rise} \equiv t_{mrr} = \frac{E_{peak}}{\left(\frac{dE}{dt}\right)_{peak}}$$

$$= t_e \quad (\textit{for an ideal exponential rise}) \qquad (6)$$

In practical waveforms, reciprocal of the maximum rate of rise t_{mrr} appears to be a better indicator of the high-frequency content in the waveform. This definition has also been applied to measured lightning current waveforms [12].

The common definition of 10 to 90% is quite often impractical. There can be a pre-pulse in the transient pulser waveform, which can make it hard to determine the 10% value. If there are some minor ripples in the waveform near the peak, there can be more than one 90% value. The definition of t_{mrr} in equation (6) gets around these issues.

For the QEXP in HEMP standards of Table 1, the interrelationships of all three risetimes (exponential, 10-90%, and maximum rate of rise) are also given by (5) and (6). Although the HEMP Standards and even some natural lightning standards are characterized by DEXP waveforms, practical pulser outputs are better modeled by the following expression [13-16].

$$V(t) = \begin{cases} V_o\, e^{-\frac{\beta t}{t_d}} \left[\left(\frac{1}{2}\right) erfc\left(\sqrt{\pi}\,|t|/t_d\right) \right] & t < 0 \\ V_0\, e^{-\frac{\beta t}{t_d}} \left[1 - \left(\frac{1}{2}\right) erfc\left(\sqrt{\pi}\, t/t_d\right) \right] & t > 0 \end{cases}$$

erfc (z) is the complimentary error function given by

$$erfc(z) = 1 - erf(z) = \frac{2}{\sqrt{\pi}} \int_z^{\infty} \exp(-t^2)\, dt$$

$$\tilde{V}(\omega) = \frac{V_0\, t_d}{(\beta + j\omega t_d)}\, e^{\left[\frac{1}{4\pi}(\beta + j\omega t_d)^2\right]} \qquad (7)$$

This analytical model of the pulser is still characterized by three numbers and has continuous derivatives. This model can be explained as follows. Consider a Gaussian waveform. An integrated Gaussian is an s-shaped waveform. When this s-shaped waveform reaches its peak, we add an exponential decay factor to it. Such a process is represented by the time domain expression in (7). Typical pulser outputs are well represented by this model. As an example, for a pulser with V_0 = 120.72 kV, t_d = risetime= 100ps, and β = risetime/decay time = 0.005, the resulting decay time = 20 ns and the maximum rate of rise for this pulser is:

$$(dV/dt)_{max} = 1.2 \times 10^{15} \text{ V/s}, \quad \text{and}$$

$$t_{mrr} = 120 \text{ kV}/1.2 \times 10^{15} = 100\text{ps}.$$

Having reviewed the unclassified HEMP standards, it is clear that all of the standards are expressed in the time domain. As a result, it is very typical for the writers of the HEMP specifications to use the standard as a specification. Time and again we have seen the procuring agencies state the specification in terms of simulating time domain electromagnetic fields over a certain volume of space with specified uniformity. There are always major differences between idealized waveforms in HEMP standards and simulated waveforms in reality. We show a comparison in Fig. 4. The use of the derivative waveform in defining the risetime as per (6) is shown in Fig. 5.

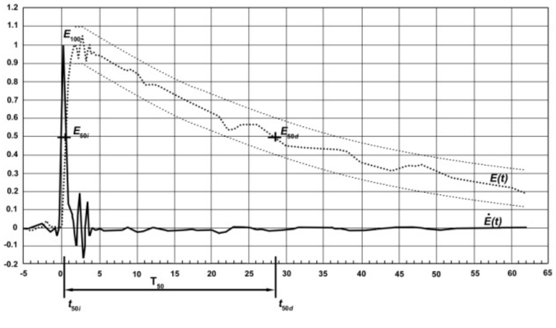


Fig. 4.Comparison of idealized and practical waveforms.

In Fig. 4, t_{50i} and t_{50d} are the times at which the waveform reaches 50 % of its peak on the initial rise and decay portions respectively. Similarly E_{50i} and E_{50d} are the corresponding amplitudes at these two instances. E with a dot on top of it is the derivative waveform.

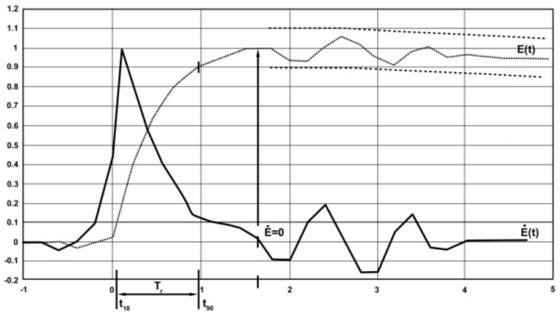


Fig. 5. Use of the derivative to define the risetime

In Fig. 5, we show the initial rise portion of the simulated waveform and its derivative.

t10 and t 90 are the time instances when the amplitude reaches 10 and 90% of the peak. The derivative waveform is used in defining the peak amplitude. The amplitude peak is reached when the derivative waveform becomes zero for the first time.

In addition, there is usually no reference to the spectral content of the simulated fields in the specifications.

- *A time-domain E1 HEMP standard (classified or unclassified) is* ***not*** *equivalent to an E1 HEMP simulator specification.*

A complete HEMP simulator specification should specify acceptable deviations of the simulated fields over the test volume, from the ideal standard (classified or unclassified) in both time and frequency domains.

This problem of incomplete simulator specification would not have arisen if the standards themselves had specifications in both time and frequency domains, including acceptable deviations from the ideal waveforms. The "acceptable deviations" appears to be an issue between the procurement agency and the supplier of the E1 HEMP simulator hardware. The standards do not address issues associated with actual simulation of these environments. The VERIFY facility [17], a threat-level sub-nanosecond E1 HEMP simulator, was the first one to use proper HEMP specifications in both temporal and spectral domains. The specification of the spectral domain for the VERIFY simulator was prescribed as: "In the frequency range from DC to 500 MHz, the spectral amplitude densities shall not deviate more than ± 6 dB from the theoretical spectrum of the double exponential pulse given in paragraph __, and not more than ±12 dB in the frequency range from 500 MHz to 1 GHz."

The reason why spectral fields are important can be stated simply as follows:

- The coupling and interaction of electromagnetic fields with a complex test object such as an aircraft, a piece of electronic equipment, a battle tank, a ship or a satellite, is *a strong function of frequency,* so it is extremely important to have all of the right frequencies, at the right magnitude, present in the incident or simulated field.

- It is entirely possible to meet the time domain specifications (peak field, risetime and fall time), but have unacceptable notches in the spectral domain. A good example of this was the deep notch at 25 MHz in ALECS [17]. The notch occurred in the electric field at the geometrical center of the working volume, and in the magnetic field quarter wavelength away. It was almost fortuitous that an electric field sensor was placed at the center point one time, and the notch was discovered. It is important to note that *the spectral notch is imperceptible in the time domain measurements, but in the frequency domain, it is very prevalent*. The reason for the notch is the presence of a TM_{01} mode in the transmission line, which cancelled the electric field of the desired TEM wave at a certain frequency and at a certain location. If the article being tested had a resonant response at the notch frequency of 25 MHz, it would not be excited at all and the test would lead to erroneous conclusions. A second example of a notch in the frequency domain was in ARES where the original Van de Graff generator had an internal anti-resonant notch, so that a certain frequency never got out of the pulser.

In this section, we have reviewed the HEMP Standards and how they have changed over four decades. The revisions are driven by improved calculations of the radiated EM fields from nuclear detonations. In addition we have traced the differences between HEMP standards and specifications. HEMP standards lead to simulation facilities that are essential in threat-level testing and vulnerability assessment. The pulse power technology had to cope with the changing HEMP standards and we describe the evolution of this technology in the following section.

III. EVOLUTION OF PULSED POWER TECHNOLOGY – USER'S PERSPECTIVE

We briefly look at a few types of transient pulse generators. With each of these types, there are specific components that affect the risetime of the output pulse. Most importantly, there is a need to minimize stray inductors and the single most critical component in determining the risetime of the output pulse is the output switch. This last stage switch in a pulse generator can be an oil switch, or a spark gap switch that uses a gas, examples of which are- Nitrogen, Hydrogen SF6 or mixtures of gasses etc.

Pulse generators for HEMP facilities typically have DC source as prime power. The time invariant voltage has to be shaped to produce a pulsed waveform that is fast rising and slowly decaying. An early review of the pulsed power is available in [19, 20]. In the 1970s and 1980s, a 10 ns risetime was practical at 100's of kV and even into several MV with ATLAS I (commonly known as Trestle) as a prime example. The types of transient energy generators are: 1) Marx generators, 2) LC generators, 3) stacked transmission lines, 4) Van de Graaffs, and 5) pulsed transformers. Of all these types, the Marx generator has become the most widely used for HEMP applications. In a typical Marx generator, several capacitors are DC charged in parallel and spark gap switches are fired to connect the charged capacitors in series. Thus high- amplitude of voltage is built before transferring energy to a load through an output switch. An improvement to a Marx circuit involves the use of either a transfer capacitor or a peaking capacitor. High currents through the spark gap of the order of 200 kA are possible with an associated charge transfer of 2 C. In HEMP pulser applications, the energy density of capacitors used in storing the transient energy is an important parameter, because weight, size and cost are all factors governing the reliability of the system. The stored energy capability of a capacitor is measured in J/cc [21]. It is noted that the energy densities have quadrupled over a period of 25 years, from 0.5 J/cc in 1984 to 2 J/cc in 2008, which now permit compact and lighter pulse power systems.

There is another important aspect of pulse power and that is the use of appropriate insulating media. Solids, liquids and gasses have been studied and used, for their ability to withstand high electric fields. Solids tend to have high dielectric strengths and used in capacitors, in the form of Mylar, polyethylene etc. Quite often, the use of solid insulators also requires a surrounding fluid (oil or gas) to combat field enhancements and corona effects. Fluids (oil and gas) as insulating media are self-healing, unlike solids. Liquid insulators are well suited for short pulses and used extensively in Marx generators. A recent pulse generator with amplitude of ~ 600 kV, risetime of 900 ps and FWHM of 25 ns [16] has used SF_6 gas as the insulating medium. This VERIFY pulser installed in the HPE Laboratory in Switzerland is shown in Fig. 6.

Fig. 6. VERIFY [17] pulser with SF_6 gas as the

The Marx stages and the peaking capacitor are in an insulating medium as seen in Fig. 6 in a transparent container filled with SF_6. This pulser drives a conical transmission line type of HEMP simulator. What distinguishes this pulse generator from many others is the use of SF_6 gas as the primary insulating medium. SF_6 gas has been extensively used for decades in providing pulse power for HEMP simulators, and also in electric power industry. However, there are disadvantages in its use that have been recently recognized [22-25]. Daout and Vega [23] consider a hypothetical case of a 1 MV Marx with a peaking circuit, for HEMP simulator. If the spark gap uses 1.4 liters or 8.8 gm of SF_6, the equivalent CO_2 production is 200 kg for a series of pulses. They claim this is equivalent to a medium sized car traveling a distance of 1,340 km. Therefore, recycling and incineration of polluted SF_6 is an option in the future, instead of releasing the gas into the atmosphere. In concluding our comments on the use of insulating gasses, it is noted that a fairly detailed study of breakdown fields of certain gasses and gas mixtures [26] has been documented. A representative measurement of the mean breakdown field of various gasses and gas mixtures is shown in Table 2.

Gas	Pressure (atm. absolute)	*Polarity*	*Peak Breakdown Field (MV/cm)*	*Mean Breakdown Field(MV/cm)*
SF6	18.3	Neg	1.86	1.35
Air	85	Neg	2.40	1.74
Air	85	Pos	2.15	1.56
N2	85	Neg	2.10	1.52
N2	85	Pos	2.10	1.52
H2	85	Neg	1.70	1.23
H2	85	Pos	1.65	1.20
15%SF6/85% Air	85	Neg	3.05	2.21
15%SF6/85% Air	85	Pos	3.10	2.25
30%SF6/70% Air	41	Neg	2.25	1.63
30%SF6/70% Air	41	Pos	2.05	1.49

Table 2. Breakdown fields for various gasses and gas mixtures for a mildly enhanced mono-cone gap [26].

Voltage polarity does not seem to make a significant difference and data is not available for positive polarity in the case of SF_6. It is very common to use SF6 spark gap switches in pulse generators for HEMP simulation.

More recently, some insulation strength measurements have been performed on a liquid called Galden®, a Perfluoropolyether (PFPE) [27]. Measured breakdown field as a function of pressure is shown in Fig. 7 and is comparable to gasses discussed above.

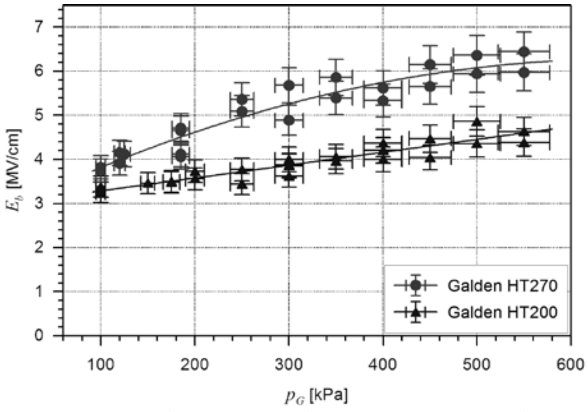


Fig. 7. Breakdown strength of two types of liquid Galden as a function of pressure.

In the last three years, ISL [27] have reached breakdown field level of 9.3 MV/cm with Galden HT270,at p_G = 1570 kPa ~ 15.25 atm for a switch gap of d = 0.30 mm. V_b = 271 kV $\rightarrow E_b$ = 9.3 MV/cm. Perhaps this opens the way to an all liquid Marx generators in the future avoiding the negative aspects of SF_6.

Returning to the subject of risetimes, since the early work of HEMP simulation in 1960s and 1970s, an order of magnitude improvement in the risetime has been realized. The risetimes were ~ 10 ns in the 1960s and now VERIFY [17] HEMP simulator is capable of 900 ps. Risetime of 900 ps is the fastest unclassified HEMP standard [8], although a risetime of 2.5 ns is a more commonly used waveform from other standards [5, 6 and 9]. Pulsers with voltage amplitudes up to 1 MV and risetimes of 200 ps are also now possible, albeit, they are not required in HEMP applications. In the beginning, the pulser requirements for HEMP simulation was in the range of 100kV to ~ 5 MV with fast rising (~ 10 ns) pulses lasting 100's of ns. Such voltages could not be switched-out in fast risetimes¸ so intermediate stages of capacitors or pulse lines were required. Switching technology (risetime related) and insulation technology for high amplitudes, required in controlling the flow of pulse power have vastly improved.

IV. SUMMARY

In this short paper, we have reviewed the evolution of unclassified HEMP Standards. E1 HEMP Standards are seen to be idealized waveforms in temporal and spectral domains. It is worth noting that $1/f^2$ decay in the frequency domain, in the standards is artificial. The standards are ideal waveforms and E1 HEMP simulators should not have to follow this behavior precisely. Perhaps the standard waveforms could be improved in the future. Also it can be noted that the E2 and E3 parts of the HEMP waveform extend (and increase) the total HEMP frequency content at low frequencies, and it is difficult to separate E1 and E2 from a theoretical point of view even though the standard waveforms display a separation. The important aspect is to ensure that simulators do not take extra efforts to mimic aspects of the standard waveforms that are not precisely correct. In practice, one has to develop E1 HEMP specifications, based on standards, to be met by practical facilities. The specifications are not the same as standards, but are based on the standards. Acceptable deviations from the standard waveforms (temporal and spectral) become important in specifying practical HEMP simulator facility performance. In Table 3, we trace the worldwide simulators [18] and focus on the evolution of risetimes. Of course, the risetime of the simulated electromagnetic pulse fields is indicative of the highest significant frequency in the waveform. The VERIFY facility in Switzerland has the fastest E1 HEMP simulated pulse with a risetime of 900 ps in the working volume.

DEDICATION

The authors wish to dedicate this note to the memory of Dr. Carl E. Baum who was instrumental in developing HEMP simulator concepts and sensors for the measurement of electromagnetic quantities. His ideas have been implemented in many nations of the world. He also advised pulse power developers on many aspects and especially on the topic of interfacing a pulser to an antenna or a transmission line.

HEMP Simulator	**Country**	**Year**	**Amplitude**	**Risetime**	**~(dV/dt) max (V/s)**
ALECS	USA	Mid 1960s	1 MV	10 ns	1.00 x10^{15}
ARES	USA	1970	4 MV	6 ns	0.67 x10^{15}
IEMP-10	Ukraine	1970	2.5 MV	20-40 ns	0.13 x10^{15}
TEMPS	USA	Early 1970s	7 MV	4-12 ns	1.75 x10^{15}
VPD -I	USA	Early 1970s	1.6 MV	5 ns	0.32 x10^{15}
EMPRESS -I	USA	Early 1970s	1.5 MV	8-15 ns	0.19 x10^{15}
ATHAMAS II -HPD	USA	Mid 1970s	4 MV	8-12 ns	0.50 x10^{15}
US Navy - HPD	USA	Mid 1970s	5 MV	2 ns	2.50 x10^{15}
ATHAMAS-I VPD -2	USA	Late 1970s	4 MV	10 ns	0.40 x10^{15}
GIN 1.6-5	Ukraine	1976	1.6 MV	5-10 ns	0.32 x10^{15}
SIEM -2	France	1979	2.8 MV	10 ns	0.28 x10^{15}
DPH	France	1980	4 MV	1-5 ns	4.00 x10^{15}
ATLAS - I (TRESTLE)	USA	Early 1980s	6-8 MV	20 ns	0.30x10^{15}
US Navy VPD	USA	Early 1980s	N/A	5 ns	Not available
EMIS-III VPD	Netherlands	Early 1980s	500kV	5 ns	1.00 x10^{14}
EMIS III HPD	Netherlands	Early 1980s	500 kV	5 ns	1.00 x10^{14}
DIESES	Germany	1981	1 MV	1-7 ns	1.00 x10^{15}
ERU -2M	Russia	1982	1 MV	2.5 -25 ns	0.40 x 10^{15}
SEMP 6M-2M	Russia	1982	6 MV	9 ns	0.67 x10^{15}
SPERANS	Sweden	1984	200 kV	2.5 ns	0.80 x10^{14}
MEMPS	Switzerland	1985	4 MV	10 ns	0.40 x 10^{15}
DM-1200	China	1985	1.2 MV	10 ns	0.12 x 10^{15}
RAFAEL	Israel	1989	2 MV	5 ns	0.40 x 10^{15}
VEPES	Switzerland	1989	800 kV	8 ns	1.00 x 10^{14}
EMPRESS -II	USA	Late 1980s	7 MV	10 ns	0.70 x 10^{15}
SAPIENS 2	Sweden	1990	1 MV	5 ns	0.20 x 10^{15}
INSIEME	Switzerland	Early 1900s	1 MV	4 ns	0.25 x 10^{15}
PULSE M	Russia	Early 1990s	600 kV	5 ns	1.20 x 10^{14}
RAFAEL- HPD	Israel	1991	600 kV	5 ns	1.20 x 10^{14}
SEMIRAMIS	Switzerland	1991	100 kV	10 ns	0.10 x 10^{14}
IEMI M 5 M	Ukraine	1992	2.5 MV	20-40 ns	0.13 x10^{15}
GINT 12-30	Ukraine	1992	4.5 MV	5-11 ns	0.90 x 10^{15}
EMIS III	Netherlands	1992	500 kV	10 ns	0.50 x 10^{14}
SEMP 12-3	Russia	1992	2.4 MV	15 ns	0.16 x 10^{15}
DREMPS	Canada	Mid 1990s	600 kV	5 ns	1.20 x 10^{14}
France Telecom	France	1996	800 kV	2.5 ns	3.20 x 10^{14}
WIS	Germany	1999	360 kV	1.2 ns	3.00 x 10^{14}
VERIFY	Switzerland	1999	600 kV	1 ns	6.00 x 10^{14}
SEMP 1.5	Russia	1998	1.5 MV	5-12 ns	0.30 x 10^{15}
TRDI	Japan	1999	300 kV	6 ns	0.50 x 10^{14}
VPD	Germany	2001	400 kV	1.2 ns	3.33 x 10^{14}
NEMP	Czech Rep.	2004	450 kV	2.5 -5 ns	1.80 x 10^{14}
MDES-60	China	2005	60 kV	3 ns	2.00 x 10^{13}
VPBW	USA	2005	N/A	1-2 ns	Not available
NOTES	USA	2005	0.1 -1 MV	3-5 ns	0.33 x 10^{15}

Table 3.Worldwide HEMP Simulators, chronologically arranged with focus on risetimes and voltage switch-outs

REFERENCES

[1] D. V. Giri and F.M. Tesche, "Classification of intentional electromagnetic environments (IEME), *IEEE Transactions on Electromagnetic Compatibility*,Volume46, Issue 3, 2004, pp 322-328.

[2] J.C. Giles and W. D.Prather, "Worldwide High-Altitude Nuclear Electromagnetic Pulse Simulators, in this special issue, *IEEE Trans. on Electromagnetic Compatibility*, March 2013.

[3]C.E. Baum, "Some Considerations Concerning Analytic EMP Criteria Waveforms," Theoretical Note 285, October 1976. Available: http://www.ece.unm.edu/summa/notes

[4] EMP Engineering and Design Principles, Electrical Protection Department, Bell Telephone Laboratories, 1975.

[5] C.E. Baum, "From the Electromagnetic Pulse to High-Power Electromagnetics," *Proc. of the IEEE*, Vol. 80, No. 6, June 1992, pp. 789-817.

[6]M. Wik, "International Electrotechnical Commission, IEC-77C," presentation atEUROREM 94, Bordeaux, France, July 1994.

[7]K-D. Leuthäuser, "A Complete EMP Environment Generated by High-Altitude Nuclear Bursts: Data and Standardization," Theoretical Note 364, Air Force Phillips Laboratory, February 1994.

[8]VG95371-10 from BundesamtfürWehrtechnik und Beschaffung, Germany (replaces Edition 1993-08)

[9] IEC 61000 2-9, "Electromagnetic compatibility (EMC) Part 2: Environment - Section 9: Description of HEMP environment - Radiated disturbance. Basic EMC publication," (1996) available at http://webstore.iec.ch.

[10] "Electromagnetic Environmental Effects Requirements for Systems," MIL-STD-464A, December 19, 2002.

[11] D.V. Giri, W.D. Prather, and C.E. Baum, "The Relationship Between HEMP Standards and Simulator Performance Specifications," Sensor and Simulation Note 538, University of New Mexico, 2009.

[12]C.Romero, M.Paolone, M.Rubinstein, F.Rachidi, D.Paonello, and D. V. Giri, "Statistical Analysis of the Risetime of the Lightning Current Pulses in Negative Upward Flashes Measured at Santis Tower", *31st International Conference on Lightning Protection (ICLP)*, Vienna, Austria, September 2012.

[13] D.V. Giri and C.E. Baum, "Temporal and Spectral Radiation on Boresight of a Reflector Type of Impulse Radiating Antenna (IRA)," chapter in *Ultra-Wideband Short-Pulse Electromagnetics 3*, ed. by Baum, Carin and Stone, Plenum Press, 1997.

[14]D.V. Giri, H. Lackner, I.D. Smith, D.W. Morton, C.E. Baum, J.R. Marek, W.D. Prather and D.W. Schofield, "Design, Fabrication and Testing of a Paraboloidal Reflector Antenna and Pulser System for Impulse-Like Waveforms," (Invited Paper), *IEEE Transactions on Plasma Science*, Vol. 25, No. 2, pp, 318-326, April 1997.

[15]D.V. Giri, J.M. Lehr, W.D. Prather, C.E. Baum and R.J. Torres, "Intermediate and Far Fields of a Reflector Antenna Energized by a Hydrogen Spark-Gap Switched Pulser," *IEEE Transactions on Plasma Science*, Volume 28, Number 5, October 2000,pp1631-1636.

[16]C.E. Baum, W.L. Baker, W.D. Prather, J.M. Lehr, J.P. O'Loughlin, D.V. Giri, I.D. Smith, R. Altes, J. Fockler, D. McLemore, M.D. Abdalla and M.C. Skipper, "JOLT: A Highly Directive, Very Intensive, Impulse-Like Radiator", *Proceedings of the IEEE, Special Issue on Pulsed Power: Technology &Applications*, E. Schamiloglu and R. J. Barker, eds., (Invited Paper), pp 1096 – 1109, July 2004.

[17] M. Nyffeler, A. Jaquier, B. Reusser, P-F.Bertholet, and A. W. Kaelin, "VERIFY, a Threat Level NEMP Simulator with a 1ns Risetime," presentation at *AMEREM 2006*, Albuquerque NM, July 2006.

[18] IEC 61000 4-32, "Electromagnetic compatibility (EMC) - Part 4-32: Testing and measurement techniques - High-altitude electromagnetic pulse (HEMP) simulator compendium", (2002), available at http://webstore.iec.ch

[19] I.D. Smith and H. Aslin, "Pulsed Power for EMP Simulators," *IEEE Transactions on Antennas and Propagation*, Vol. AP-26, No. 1, January 1978, pp 53-59.

[20] I.D. Smith and H. Aslin, "Pulsed Power for EMP Simulators," *IEEE Transactions on Electromagnetic Compatibility*, Vol. EMC-20, No. 1, February 1978.

[21] J.R. MacDonald, M.A. Schneider, J.B. Ennis, F.W. MacDougall, X.H. Yang, "High Energy Density Capacitors," *IEEE Electrical Insulation Conference*, Montreal, Quebec, Canada, 2009.

[22] M. Rigby et al., History of Atmospheric SF_6 from 1973 to 2008, *Atmos. Chem. Phys*., Vol. 10, 2010, pp 10305-10320.

[23] B. Daout and F. Vega, "SF_6 for High-Voltage Pulse Generators, an Ecological Analysis," presented at EUROEM 2012, Toulouse, France, July 2012.

[24] J. Blackman, M. Averyt, and Z. Taylor, "SF_6 Leak Rates for High-Voltage Circuit Breakers – U. S. EPA investigates Potential Greenhouse Gas Emissions Source," (2006), available at: http://www.epa.gov/electricpower-sf6/documents/leakrates_circuitbreakers.pdf

[25]"Byproducts of Sulphur Hexafluoride (SF_6) Use in the Electric Power Industry," prepared for U. S. EPA, January 2002, available athttp://www.epa.gov/electricpower-sf6/documents/sf6_byproducts.pdf

[26] V. Carboni, H. Lackner, D.V. Giri, and J. Lehr , “The Breakdown Fields and Risetimes of Select Gasses under Conditions of Fast Charging (~ 20 ns and less) and High Pressures (20-100 atmospheres),” Switching Note 32, University of New Mexico, 1 May 2002.

[27] R. Bischoff, Ph. Delmote and S. Pinguet, “HPEM Research at Institute Saint-Louis,” Personal communication, October 28, 2011.