DEVELOPMENT OF A HIGH VOLTAGE ARBITRARY WAVEFORM GENERATOR CAPABLE OF SIMULATING THE NATURAL ELECTRIC FIELDS ARISING FROM STEPPED DOWNLEADERS

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Abstract: In this paper we describe the main features of a new prototype, high voltage, arbitrary waveform generator. The generator is capable of precisely simulating the rapidly escalating electric field due to a lightning downleader, including the well-known steps or pauses as the leader progresses toward its point of attachment near the ground. It utilises a computer controlled interface that drives a set of series-stacked flyback transformers. The resulting output is any desired (montonically) increasing waveform, downloaded from the computer.

1. Introduction

Research into direct-strike lightning protection design and, specifically, comparative air terminal performance, is usually conducted by one of three means: (i) "natural" field experiments where air terminals are placed in locations of high lightning incidence [1, 2], (ii) "artificial" field experiments where air terminals are exposed to lightning triggered by rockets [3, 4], and (iii) laboratory experiments using high voltage impulse generators [5, 6, 7, 8].

The last of these is an attractive option because testing of air terminals on demand can provide results much more quickly than having to rely on the vagaries of field testing. However, progress in the laboratory has been limited for a number of reasons. One problem relates to the scaling of results from the laboratory to the field, although some aspects of this limitation can be overcome by performing a large number of systematic experiments. A more difficult problem derives from the fact that the Marx-style impulse generator [9, 10], which is used in most high voltage laboratories around the world, produces an RC-type waveshape. Hence, these generators are unable to simulate the temporal electric field waveforms evident in natural lightning phenomena. The natural field at ground level has two components: a "permanent" (or DC) and an "impulse" component. The latter component is a rapidly escalating waveform for a nearby lightning strike [11] which cannot be reproduced by the present generators. Researchers have attempted to circumvent this problem by using switching impulses and a peak voltage for a given terminal-plate gap such that the field risetimes are similar to those observed in nature, namely ~ 1 kV/m/μs [6]. However, this practice disregards the importance of the build-up to breakdown and the role it plays in air terminal performance. This is particularly so in non-conventional air terminals that rely on capacitive coupling to a downleader in order to gain the necessary energy for their operation. A comparison of the basic waveforms is shown in Figure 1.

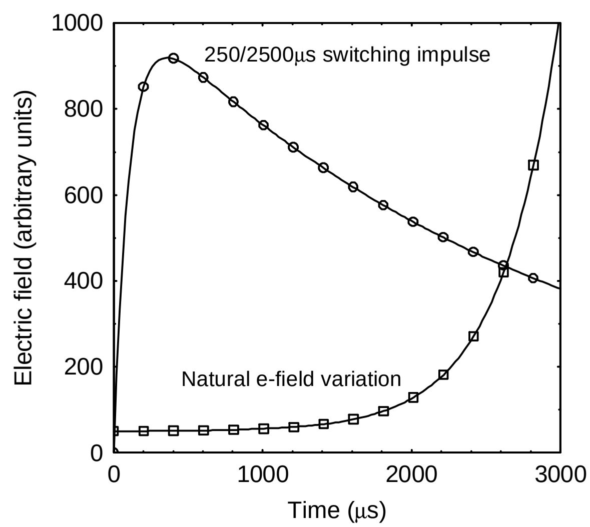

Figure 1: Comparison of waveform obtained from Marx-style generator with that observed in nature from a progressing lightning downleader.

Figure 2 shows an active air terminal configuration designed to operate like the "Trigatron" in the firing mechanism of a Marx generator. The main difference in this configuration is that energy is derived from the approaching leader and not from a laboratory power supply. In the pre-stroke period with electric fields around 10-20 kV/m, the floating sphere will collect random ions. These are passed to ground through the impedance which couples the sphere and earth rod. Under these conditions, and even in the early stages of leader approach, the sphere remains effectively grounded and presents a spherical surface of low field intensification. This acts to preclude corona and space charge formation.

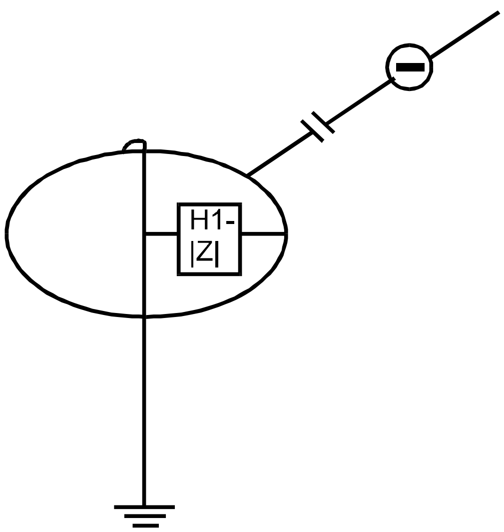

Figure 2: Basic design of a corona reducing, capacitively coupled air terminal.

However when the field is increasing at a rate approaching 1 kV/m/μs due to an approaching downleader, the capacitive reactance due to the coupling decreases and current attempts to increase. However, the presence of the impedance Z restricts the flow of displacement currents. This causes the sphere to rise in potential until a triggering arc is created across the gap between the sphere and the earthed rod.

Should triggering occur too early, a failed streamer will leave space charge above the terminal, and this will act to reduce the local field strength. Testing with a Marx generator can give very misleading results because the highest dV/dt occurs at the commencement of the pulse and there is no trigger when peak voltage is being approached since dV/dt approaches zero.

Figure 3(a) shows how testing with a Marx generator produces very early triggers when voltage is impossibly low to form a streamer. The figure shows how the rate of pulse repetition progressively reduces with time as the dV/dt reduces. At the current peak, dV/dt is zero and no triggering arc can occur.

Conversely, with the natural lightning waveform, trigger pulses hold off until dV/dt rises to an adequate value. Thereafter, pulse rate actually increases with the increasing field strength, as shown in Figure 3(b). Streamer generation is actually retarded until the near field has adequate strength to support streamer formation. It is readily seen that the Marx generator waveform is totally unsuited for testing this type of terminal.

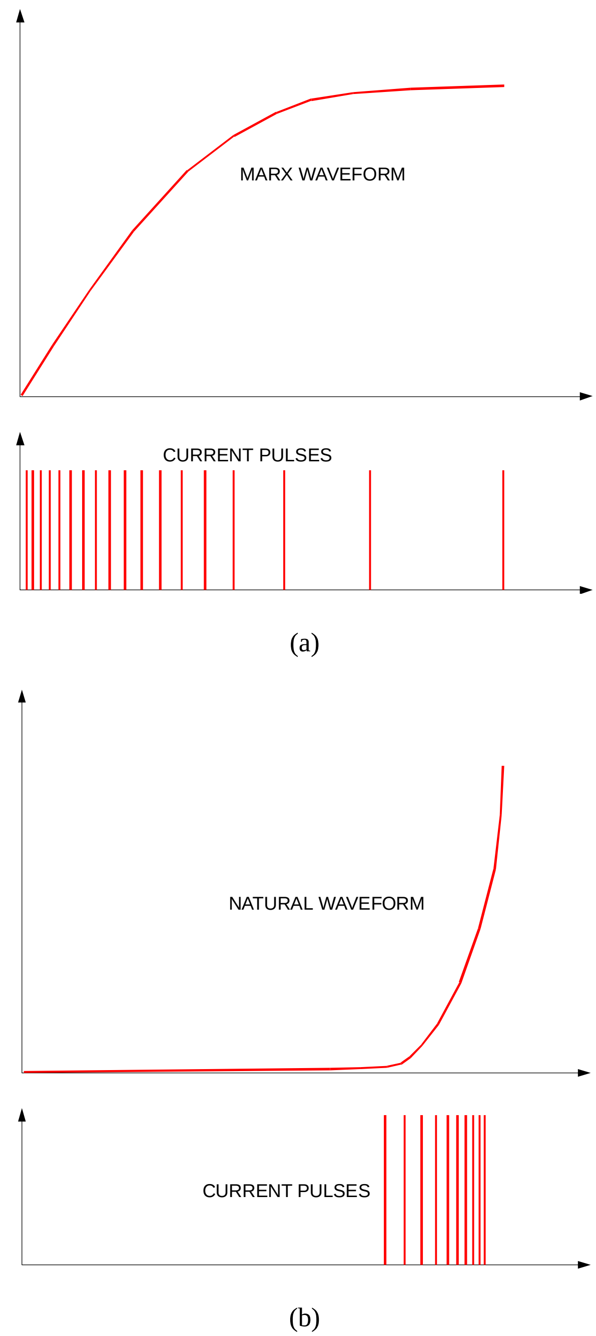

Figure 3: (a) Early triggering due to a typical Marx-style switching impulse waveform; (b) Delaying triggering that would actually occur under natural conditions.

In the remainder of this paper, we describe the main features of a new prototype, high voltage, arbitrary waveform generator. The generator is capable of precisely simulating the electric field due to a lightning downleader, including the well-known steps or pauses as the leader progresses toward its point of attachment near the ground (Figure 4).

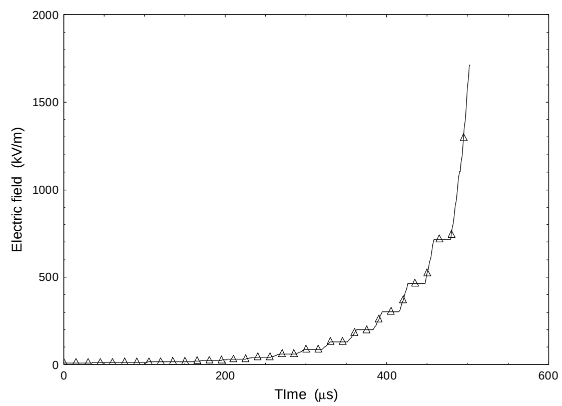

Figure 4: Simulated electric field waveform at the ground from a stepped downleader.

2. Generator Design

A block diagram of the mechanical design of our 10-stage, 200 kV prototype system is shown in Figure 5. The key to the whole concept lies in the combined effect of series stacking a number of specially tailored transformers. The generator is capable of accurately simulating any monotonically increasing waveform, such as the electric field due to a stepped lightning downleader.

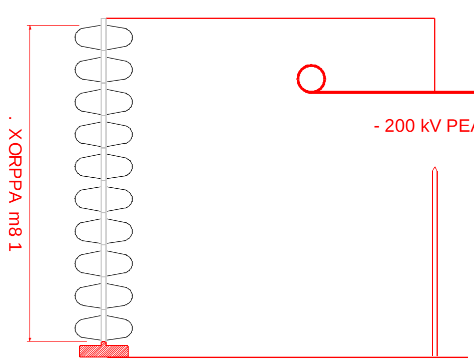

Figure 5: Mechanical design of the new high voltage generator.

A personal computer installed with a high speed digital I/O card is used to output a 10-bit data word which is a pulse width modulated (PWM) representation of the rate of rise of a point on the desired waveform. Typically, the PWM frequency is 100 kHz and the data rate is 2 MHz. This enables a PWM resolution of 5 %. Hence, it allows delays to be inserted between each bit in the data stream in 5 % steps in order to create a ripple effect. A simple example of this "interleaving" principle is illustrated in Figure 6.

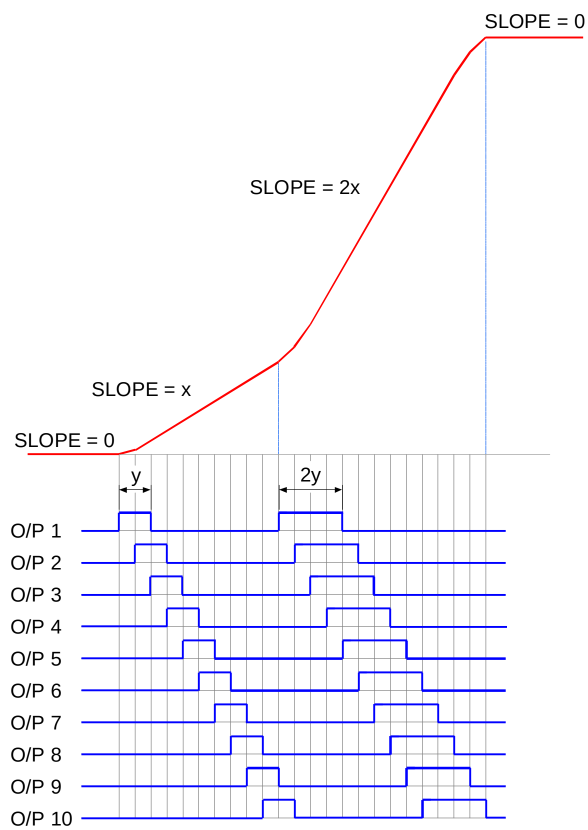

Figure 6: Simplified example of the interleaving principle of the generator. The waveform slope is approximately proportional to the duty cycle.

Each delayed bit of the output data is passed into one of ten opto-driven cables as shown in Figure 7. Each of these fibre optic signals is then passed into an isolated switched-mode power supply (SMPS) with its own floating DC power supply. The fibre optic signals are converted back to electrical form inside the SMPS's.

The output stage of the generator uses transformers configured in a flyback topology to eliminate the need for output inductors. When the transformer primary winding switches are activated by the amplified SMPS outputs, the primary side of each transformer acts as an inductor due to the blocking action of the output diode. When the switches are deactivated, the voltage reverses and the inductive energy stored in the primary is released through the secondary winding. The output diode then conducts so that a negative voltage appears on each output.

Risetimes > 1 kV/μs are achievable with this system. The advantage of series stacking the modules comprising the generator is that each module only needs to be able to output a voltage of V_{out}/n and, more importantly, output it at a rate of only $1/n$ of the required slew rate, where n is the number of modules. An additional benefit of increasing the number of modules is that the ripple effect from the interleaving is smoothed even further.

Each power unit in the prototype can produce up to 20 kV with a series stack of 10 units reaching an output voltage of 200 kV after additional filtering. Also, each unit can maintain a constant voltage output, thus allowing the waveform to rise from a predetermined static level. At this stage, no attempt has been made to control the current waveform of any subsequent air discharge. The prototype has been designed to simulate only a millisecond or so immediately prior to the return stroke of a discharge.

Other advantages of this system include: (i) the test waveform can be changed from concave, to linear, to convex in a relatively short period of time (of the order of minutes) so that empirical corrections for variations in temperature, pressure and humidity are not needed; (ii) computer control means that the waveshapes can be stored and recalled at any time to repeat a test.

3. Preliminary tests

The prototype generator has a design objective of producing a variable, programmable wavefront with 200 kV peak voltage. Accordingly, the authors have no expectation of creating an upward *leader* in the laboratory. This may come at a later time using a full size generator based on our experience with this prototype. We do, however, expect to generate *streamers* and to break down a gap with these streamers.

Notwithstanding these limitations, we expect some useful testing to be performed. We currently propose to:

- compare sharp and blunt rods with and without prior corona producing fields
- test sharp and blunt rods with both concave and convex waveshapes
- test capacitively coupled air terminals under different wavefronts to optimise their triggering time with respect to absolute field strength and rate of rise of the electric field
- compare streamer generation from active terminals and passive sharp/blunt rods.

The authors believe that a true streamer-to-leader transition will not be observed with a generator producing less than 1 MV. Of course, the voltage required to observe this transition is not known with any certainty. All past testing with Marx generators has a progressively reducing rate of rise of electric field from t = 0. At the time the generator has reached the general area of the critical breakdown voltage, the dV/dt is considerably reduced.

On the other hand, this generator produces the typical waveform observed in nature and hence causes a streamer to be launched into a sustainable electric field strength, at a time when the rate of rise is rapidly escalating. It could quite easily be observed that no change in the time to breakdown is recorded, but systematic tests are required to prove this.

4. Conclusions

This paper has described a new design of high voltage generator that is capable of producing a waveform that faithfully replicates the type of lightning electric field waveform observed in nature. The generator tests presently in progress are part of a broad program of lightning protection research also involving computer modelling and field testing. The results will be published as soon as they become available.

We aim to increase the capacity of the generator to ≥ 1 MV. If this is achievable, it will revolutionise lightning downleader simulation experiments in general and, specifically, comparative air terminal testing in the high voltage laboratory.

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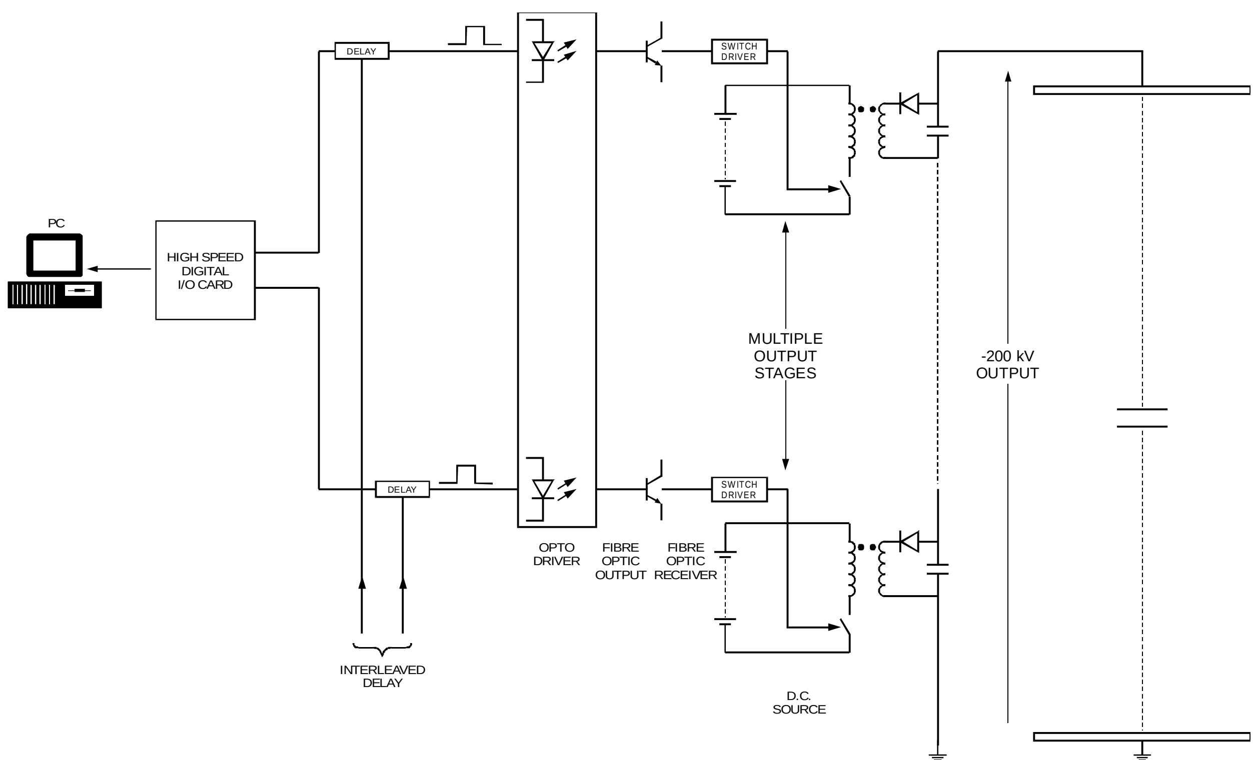

Figure 7: Diagram of the prototype 200 kV high voltage arbitrary waveform generator.