Transients in "constant-current" generators¹

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Some shock-generator circuits may deliver large transient surges at onset and termination. The sources of these surges are derivable from electromagnetic analysis of the circuits employed. Virtual elimination of the surges may be accomplished by a simple rearrangement of the switching portion of the circuit.

Many Es report the use of homemade "constant-current" shock devices to deliver aversive stimulation. In the typical unit, 110-V ac is used to power a step-up transformer. Approximation to a constant-current generator is achieved by placing a resistor in series with the S which is large in comparison with the resistance offered by the S. Shock is delivered, usually by switching on the secondary side of the transformer. It has been known for some time that there is the possibility of transient surges when switching in this type of circuit (Muenzinger & Walz, 1932; Forbes & Bernstein, 1935). The purpose of this paper is to show the bases for these transients and to describe a simple way to markedly reduce these sources of stimulus variability.

The essentials of the circuit described above are presented in the upper panel of Fig. 1. We are dealing here only with the case of two electrodes that are directly attached to the S. Circuits that use a scrambling device at the output require separate consideration. The series resistor (R_1) is chosen so that the desired current is delivered across the S (R_2). Operating the relay (R_y) switches both resistances into the circuit simultaneously. Oscilloscope tracings of a comparable circuit, in a bench test with a carbon resistor simulating the S, indicated transient surges on both shock onset and termination. These transients were large and of relatively short duration, making it difficult to detect them without special equipment such as an oscilloscope

that permits intensifying that small portion of the sweep trace in which the transient occurs. Electromechanical meters, commonly used to monitor shock intensity, have inherently slow response speeds that preclude detection of these surges.

There are two separate sources of transients in the type of circuit described in Fig. 1. One transient derives from the fact that most, if not all, available resistors are not ideal components. A more complete depiction of an actual resistor is presented in the lower panel of Fig. 1. The capacitive aspect of the series resistor acts as a high-frequency short circuit. This means that when the relay is operated, the instantaneous value of the transformer secondary voltage is momentarily transmitted, almost unattenuated, across the S before the low-frequency resistance begins to attenuate the output. If the secondary voltage happens to be crossing zero, no transient will ensue, but if switching occurs at the peak in the sine wave, the peak value is transmitted.

A second kind of transient occurs at shock termination and is derivable from electromagnetic considerations of switching in inductive circuits (see, for example, Kraus, 1953). It can be shown that when an inductive circuit is interrupted, a voltage surge is generated in accordance with the following formula:

$$e = L \frac{di}{dt}$$

where e = voltage, L = inductance (in henrys), and di/dt = the rate of change of current with time. In the circuit described in Fig. 1, L is determined by the inductance of the transformer secondary.

The surge voltage, e , is proportional to the rate of change of current with time, multiplied by the inductance, which, for the present discussion, may be considered constant. Since the instantaneous current change at shock termination varies in this type of circuit due to the randomness of switching times (i.e., shock delivery is not synchronized with the line current), it may vary from zero to the peak of the ac current. In this circuit, as the relay contacts begin to open at shock termination, energy stored in the inductive source compensates for the drop in current, causing an electromotive surge that arcs across the air gap between the moving contacts. If the break occurs at zero current, the resultant voltage must be zero ($di = 0$); but at peak values, large surges ensue.

The above discussion has several implications: (1) If a standard telephone type of relay is used, both transients discussed will contribute to surges at shock onset. This is because such relays usually exhibit "contact bounce," which means that there are several makes and breaks before the contacts settle firmly in place. Each make contributes the first type of transient, and each break contributes the second type of transient. For example, a 24-V dc relay (Allied Control, Type TF 154), examined in a bench test, had a settling time of .3 msec on make, with a number of bounces before coming to rest. (2) The current-breaking time of the relay affects the denominator of the equation (dt). In effect, the faster the relay, the larger is the transient. (3) Contact pitting will affect the transients because it will affect the localized electric field and the area across which arcing occurs.

There are several ways to reduce or eliminate these transients. If shock onset occurs at zero voltage and if termination occurs at zero current, both types of transients are eliminated. Synchronizing

Fig. 1. Upper panel: Schematic representation of a typical "constant-current" shock source; not shown are protective fuses, power switch, etc. Lower panel: Schematic representation of the electrical characteristics of a typical resistor.

Fig. 2. Schematic of proposed modification of shock source to reduce switching transients.

operation of the relay with the secondary voltage and current may be accomplished but requires additional circuitry that must be tailored to the specific switching relay chosen. A simpler solution to these problems is offered by a trivial rearrangement of the switching circuit. Instead of using the normally open contacts of a relay to switch both the series resistor and the S into the circuit at shock onset, the normally closed contacts of the relay are used to short out the S until shock delivery. This arrangement is shown in Fig. 2, and it can be seen that operating the relay merely switches the S into the circuit, and that the series resistor represents a constant load on the secondary of the transformer. The latter fact eliminates the onset transient since there is no possibility for the kind of capacitive short circuit as in the first arrangement. The termination transient is affected by the magnitude of the current change in this inductive circuit. To the extent that the electrical loading of the transformer is constant, this current change (di) is minimized. This current change can be computed as the difference between the steady-state current with the series resistor

considered above and the current flowing with the S and the series resistor both in circuit. Thus, although a voltage surge may still occur, it will be considerably reduced in comparison with the first circuit.

To demonstrate these effects, we conducted a bench test with the two types of circuits. The same components were used in the two configurations described in Figs. 1 and 2. Line current (110 V ac) was first stepped down to 25.7 V ac by a Variac. This was then stepped up to 351 V ac (rms) by a transformer (United Transformer Corp., CG-302). Carbon resistors were used as the series resistor (150 K ohms) and to represent the S (5.1 K ohms). The current output, therefore, was approximately 2 mA. A telephone type of relay (Allied Control, TF-154) was used as a switch in the two circuits. To obtain photographs of the oscilloscope tracings of the voltage across the dummy S, we pulsed the relay (duration = approximately 40 msec) at a rate of about 10/sec and opened the camera shutter long enough to obtain 20-30 sweeps. Relay operation was synchronized so that shock onset was approximately at the peak of the ac

waveform. Since transients show up as faint traces, we intensified the portions of the sweep during the onset and termination transients.

The results of this test are shown in Fig. 3. The photograph on the left was obtained with the circuit of Fig. 1; the one on the right was obtained with the circuit of Fig. 2. The transients exhibited by the first current were two to three times the nominal current value. In the right-hand photograph, the white streak at the termination of shock resulted from contact bounce of the relay in returning to the normally closed position. A relay with mercury-wetted contacts would have eliminated this effect.

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Fig. 3. Photograph of oscilloscope tracings of current through the shock circuit, including the dummy S. The picture on the left was obtained with the circuit depicted in Fig. 1; the one on the right was obtained with the circuit depicted in Fig. 2.