An Accurate Ramp and Stair Step Source

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Abstract

This describes a method of producing extremely linear ramps or multiple steps of well defined amplitude waveforms by modifying a single step pulse. The basic circuit uses lengths of coaxial cables and resistors to transform a single step into two steps with in/out impedances matched to the cables and resistors. Multiple circuit sections can form multiple stair-steps or a ramp of sub-nanosecond to microsecond in length, with mV or kV amplitudes. Amplitudes and times are limited only by the coaxial cable and resistor maximum voltage capabilities and trimming lengths.

I. Two Step Waveform Circuit

This circuit converts a one step pulse into a two step pulse with unique characteristics. The two steps have equal amplitude and the time between them is determined by two equal length coaxial cables. The basic circuit of this new invention and the two step resulting waveform are shown below.



Figure 1. Basic Stair-Step forming circuit



Figure 2. Input and Output waveforms

Half the amplitude of the applied step function is delayed for a short time while the other half flows directly to the output. The input to the circuit is a combination of two parallel 100 ohm sections which provide matched 50 ohm impedance at the input. The 50 ohm resistor R1 is in series with the grounded shield 50 ohm coax, the combination of which is 100 ohms. The floating shield coax at the top is in series with the 50 ohm output impedance, which together provide 100 ohm impedance.

The impedance looking back into the circuit from the output is also matched with the 50 ohm resistor R2, which provides a matched circuit for reflections from the output. The two identical length 50 ohm coaxial cables determine how long the half amplitude is delayed until it increases to its full amplitude. When the 50% of the input pulse travels down both cables, their voltage is reflected back to the input. The voltage on the 50 ohm coaxial cable which is at its far end is reflected in the opposite polarity while the voltage on the open circuited coax is reflected in the same polarity.

Their combination causes the voltage at the output terminal to increase to its full 100% amplitude when the reflections return.

The 50 ohm resistor O1 absorbs part of the input pulse until the open circuit coax is charged. The 50 ohm resistor R2 is only active for reflections from the load. This basic circuit is symmetrical and operates in the same manner when the input is applied to either end.

The precision of the 50% amplitude depends on the equality of the 50 ohm output cable impedance and the 50 ohm resistor resistance. The risetime of the 50% step and the 50% to 100% step primarily depends on the resistor maintaining its 50 ohm impedance during its time of rise. These circuits should be constructed maintaining minimal physical length at the junctions of the input to the resistor and coax cables and to the output connection. Careful match to 50 ohms impedance minimizes reflections and short connections add minimal delay from input to output.

II. Multiple Stair Step Waveforms

Adding (n) sections in series produces 2^n steps. The coax of each added section is half the length of the previous section with the resistors retaining a value of R.

The circuit in Figure 3 adds 2 more, two step circuits to the example in figure 1. Each added section doubles the number of steps.



Figure 3. Multiple two step circuits in series

The circuit in figure 3 produces 2^3 or 8 stair steps as shown below in figure 4.



Figure 4. Three, two step sections creates 8 stair-steps

Because each circuit is passive and matched at both input and output, any number of circuits can be added to produce 16, 32, or 64 steps. We identify a series of two step circuits in series together as a module.

III. Ramp Waveform

When the lengths of multiple stair-steps are shorter than the input step risetime this circuit will produce a very linear ramp waveform. The number of steps also determines the amount of ripple in the linear part of the ramp. By making the shortest steps much shorter than the risetime of the input step function a very smooth linear ramp waveform is produced.



Figure 5. Ramp linearity effects.

The pulse risetime can be spoiled to about twice the minimum step time to provide a smooth ramp. Matching the resistance of the resistors to the impedance of the coaxial cables and the output impedance, the output waveform becomes a very linear ramp.

Voltage remains on the coaxial cables as long as the input pulse voltage remains. At the end of the pulse a decreasing ramp is formed with the same fall rate as the rising ramp. The basic effect is shown in Figure 6.



Figure 6. Ramp fall is identical to the rising ramp

Rising stair-step waveforms will also exhibit falling stair-steps at the falling edge.

IV. Nonlinear Effects at Start and Finish.

The number of stair-steps determines the ramp linearity at its beginning and end. If the input pulse has an approximately Gaussian risetime, its beginning and ending are smooth transitions to the limited linear portion in the middle of its amplitude. The ramp linearity requirement at its beginning depends on the number of steps that reduce the amplitude of non-linear beginning and ending.

Each added section cuts the nonlinearity of a ramp where the ramp begins and ends by a factor of two. Increasing the number of steps to 16, 32, or more, can form ramps that are very linear from 1% amplitude to between 90 % and 99% of its maximum amplitude. Coax skin effect losses degrade ramp linearity at the top end similar to how skin effect losses slow the top of a rising pulse. This becomes significant when long coax is used to produce slower ramps.



Figure 7. Linear 80 ns ramp with 2250 V amplitude

The measured waveform of a long ramp in Figure 7 shows the total skin effect losses after the 80 ns long ramp has ended. The total electrical length of coax used in a ramp module is almost as long as the ramp. This ramp module has almost 80 ns of RG 402/U; which has silver plated copper IC, solid Teflon insulation inside 0.141 inch

O.D. solid copper tubing. Skin effect losses in the coax have a significant effect on step risetimes but only affect ramp linearity at its top few percent.

V. Stair-Steps and Ramps from mV to kV Being completely passive this circuit can produce stair-steps and ramps that operate up to the maximum rating of the coax and/or resistor for the length of time the voltage is applied.

VI. Coaxial Cable Impedance and Resistor Values

Commercial coax is seldom exactly 50 ohm impedance. Uniformity of coaxial cables impedance in each module determines stair-step amplitude and ramp linearity. The coaxial cable impedance should not vary along its length, and must also match the output impedance. For maximum linearity a controlled resistance attenuator at the output will improve the coaxial cables impedance match. The coax should be measured when cutting to their required length.

Matching resistor resistance to the impedance of its associated coax provides uniform step amplitudes or linear ramps. Resistors should have minimal parasitics to retain input pulse risetimes for short stair-step operation. Minimizing resistor parasitics requires that they are enclosed in housings to maintain its correct impedance along its length. This is especially true for long resistors necessary for high pulse voltage operation. Attenuator patent #3,665,347 of 1972 describes techniques for housing resistors which control their impedance to picoseconds. [1]

The voltage coefficient of resistance of the resistors used in these circuits must also be considered when ultra linear ramps or very uniform stair-steps amplitudes are produced at kilovolt levels. It is important to control these two resistor parameters when producing high voltage sub nanosecond ramps and stair-step waveforms. Allowable impedance variations will be determined by calculation and measurement as these ramps are produced.

VII. Isolation of Floating Coax

Ferrite toroids are placed around the floating shield coaxial line at its input and output connections to prevent currents from flowing on the outside of the outer conductor. This forces the current to flow only inside the outer conductor. Currents that flow on the outside of the outer conductor do not return to the circuit and degrade step risetime when they are lost. The inside diameter (I.D.) of the ferrite toroid should be close to the outside diameter (O.D.) of the coaxial cable outer conductor to prevent small amounts of current from sneaking through the narrow gap and being lost. Locating the outer conductor some distance from nearby ground potential conductors also reduces high speed displacement currents to help maintain stair-step risetimes. Patent #7,449,637 of 2008 describes methods of using special conical shape ferrites which minimize the amount of capacitance added by the high dielectric constant ferrite materials. The smallest diameter ferrite impedes the highest speeds which has the greatest shunting effect at the highest speeds. The ferrites minimize the displacement current shunting effect to ground on the long coaxial cables. This provides minimal high speed losses. [2]

VIII. Resistive Source Testing Advantages

The ramp modules use special resistors and commercial coaxial cables instead of reactive inductors and capacitors. Using a resistive impedance pulse source generator and the resistive impedance ramp modules minimizes the effort to analyze the effects of non-linear response loads subjected to a ramp waveform. Energy reflected back into the reverse matched ramp modules and reverse matched pulse sources will not be returned to the DUT as occurs with circuits that shape pulses with reactive components.

IX. Multiple Stair-Step and Ramp Rates

Because each two step circuit adds minimal time delay and loss, additional half step sections can be switched in or out to reduce, or increase, the ramp rate of rise. The Ramp time can be doubled (slowed down) by a factor of 2 by adding a two step section that has twice the coax length of the longest half step section in a circuit. Switching in progressively longer sections can reduce ramp times by factors of 2, 4, 8 or more, while retaining linearity.

Longer ramps will not be negatively affected by non-50 ohm impedance switches with short risetime discontinuities needed to maintain high voltage standoff.

X. Lower Impedance Circuits and Modules

Lower source impedance step function pulse sources, with parallel arrangements of widely available 50 ohm coaxial cables, permit lower impedance ramp module construction. Simple parallel sections at 25 ohm, 12.5 ohm, 16.67 ohm, 10 ohm, 8.3 ohm etc. with matching resistor values are possible for whatever impedance is needed for linear ramps.

Longer ramps can be constructed by using some sections of lumped constant transmission lines instead of coaxial cables. This can reduce the amount of coaxial cable required. However the inherent value of producing ramps and stair-steps in the 100 ns and shorter time frames has significant value.

XI. Conclusions

Presently there are many applications for relatively slow ramp rates. The ability to produce accurate amplitude high speed stair-steps and high voltage high speed ramps opens new measurement possibilities and applications. Linear ramps for streak cameras were our original application, but many additional applications are possible now that these circuits are available. Testing of Component failure levels or dV/dt sensitivities, magnetic saturation levels of ferrites at high dI/dt rates are just two early applications for high voltage ramps. Producing these waveforms in 50 ohm impedance allows them to be located near; but not adjacent to high speed circuit applications with minimal high speed degradation. The ability to produce these waveforms at high voltage opens additional possibilities that will take some time to materialize.

Accurate stair step waveforms and high voltage ramps possible with this basic circuit will become a new reference source for analyzing linearity of digitizers, scopes, A to D and D to A converters. These simple passive circuits constructed with reliable resistors only require an initial calibration when used as reference standards.

Using the stair-step waveform eliminates the requirement to pick out precisely located points on a ramp for time/and or amplitude measurements. This waveform provides a much improved analysis tool for scope or digitizer linearity measurements.

As accurate stair-step and ramp waveforms from picoseconds to microseconds become known, useful applications will develop.

Applying a linear ramp to an amplifier and differentiating the output is a sensitive method of

measuring its linearity. A very old application in reference #3 provides a detailed explanation of this technique. It requires high speed RC type differentiators which is simple to construct for short time constants. Ramps used for pulse charging of capacitors also provide advantages in charging time and efficiency.

An interesting effect occurs when placing two ramp modules of the same ramp time in series. The result is a very smooth transition rising waveform that is not exactly; but quite Gaussian like. It has the added advantage that it is perfectly matched and has no reflections from either end.

We have applied for a patent on this basic circuit and its applications for the ramp and stair-step arrangements described above.

It may be coincidental that our development of this circuit which uses 50 ohm coax and 50 ohm resistors was produced during our 50th year in business.

References:

- [1] Patent # 3,665,347, 1972
- [2] Patent # 7,449,637, 2008
- [3] S. Kramer; "A Sensitive Method for the Measurement of Amplitude Linearity"; Proc IRE, Aug, 1956; pp 1059-1060.

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