AN IMPULSE GENERATOR SIMULATION CIRCUIT

by

Steven E Meiners

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This thesis was presented

by

Steven E. Meiners

It was defended on

November 25, 2002

and approved by

J. R. Boston, Professor, Electrical Engineering

H. K. Kim, Professor, Electrical Engineering

Thesis Advisor: R. G. Colclaser, Professor, Electrical Engineering

ABSTRACT

AN IMPULSE GENERATOR SIMULATION CIRCUIT

Steven E Meiners, MSEE

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This thesis describes the creation of a simulation circuit to match the output of a Marx type Impulse Generator. The goal was to estimate the stray capacitance and insert that capacitance into the simulation circuit to effectively produce an output similar to that of the generator. An actual three-stage impulse generator was used as the base. Several different levels of impulse voltage were tested, and the output waveforms were captured. Research was conducted to formulate the stray capacitance and identify the locations of these capacitances in the generator itself. The simulation circuit was then subjected to several iterations, adjusting the capacitance values to attain an output as close as possible to that of the actual generator.

Conclusions of the research indicate that an effective simulation circuit can be created to give an output that is close to, but not exactly that of, the actual generator. In the research, several areas of error were identified in the actual generator that were not present in the simulation circuit. These areas are discussed in the thesis.

ACKNOWLEDGEMENTS

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1.0 HISTORY AND BACKGROUND

1.1 Introduction

The purpose of this research is to develop a SPICE(1)* simulation circuit that will generate a Marx-type Impulse Generator (IG) output wave shape. To conduct this study an existing IG set at the Cutler-Hammer Technology & Quality Center (TQC) in Pittsburgh will be utilized for the experimental results and the base for the simulation to match. This being the case, the calibration of this IG will also be consulted for the various correction factors on this equipment. This calibration is performed yearly by Dr. Roy Voshall of Gannon University. The Cutler-Hammer IG is used to perform design testing of electrical distribution equipment rated from 600 to 38000 volts.

Full wave and chopped wave impulse tests are methods to demonstrate the ability of high-voltage equipment to handle lightning strikes and switching overvoltages, as defined in IEEE Standard 4.(2) In order to evaluate the complete capability of the equipment to withstand these surges, the entire waveform is required. The full waveform can be captured and used in this evaluation by the use of an oscilloscope and a voltage divider.(3) A calibration method is used to maintain the test equipment and certify its ability to perform this testing; this method is IEEE Standard 4.

There are many factors that lead to error in the measured impulse waveform. The IEEE Standard 4 is meant to maintain a level of acceptable quality in the testing. Each impulse system is typically tailored for the class of equipment to be tested.

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* Parenthetical references, placed superior to the line of text, are given in the bibliography.

The Cutler-Hammer system at TQC in Pittsburgh is primarily used for a maximum of 38kV class of equipment and levels of 200kV impulse. The waveform, Figure 1, is the standard 1.2 x 50μs duration with the peak voltage reached in 1.2μs (T1) and the tail of the wave decaying to a level of 50 percent of the peak in 50μs (T2).

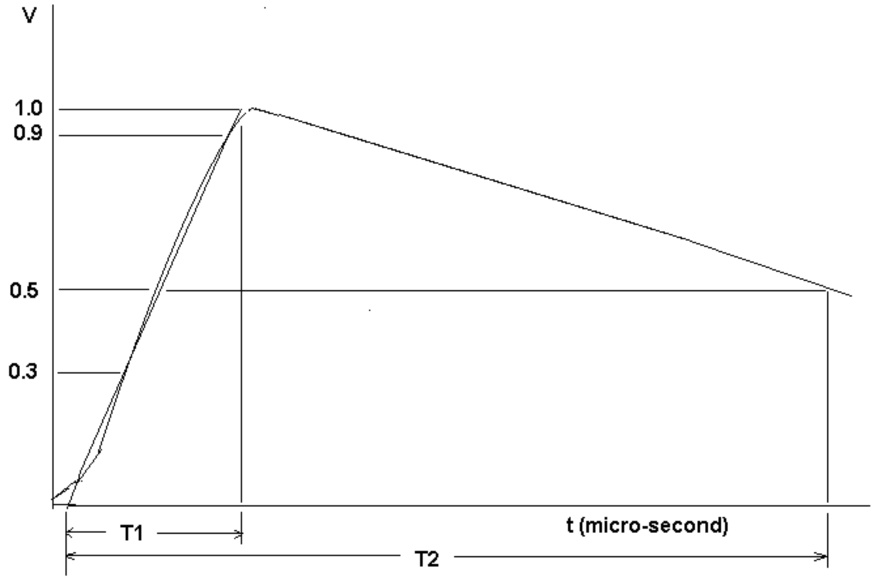

Figure 1 Standard 1.2 x 50μs Waveshape

1.2 Background of High Voltage Impulse Testing

The multi-stage impulse generator uses several capacitors charged in parallel. These capacitors are then discharged in series to achieve higher voltages from a relatively low voltage source. The capacitors are discharged by use of spheres, which act as switches. This design was credited to E. Marx in 1924.(4) As a result; the multi-stage generator is commonly referred to as a Marx generator.

Referring to Figure 2, the operation of the multi-stage generator can be described as follows. All capacitors, one in each stage, are charged to a voltage V relative to ground. The bottom sphere gap is triggered by voltage injection and breaks down, discharging that stage capacitor. Subsequently, the remaining stage gaps also break down, discharging each stage capacitor. The result is a cumulative swing in voltage from zero to nV, where n is the number of stages in the Marx generator. The impulse generator used in this research is a three-stage unit capable of 300kV peak.

The sphere gaps act as switches. Once the first gap breaks down, the capacitor swings from V to zero, see point A Figure 2. This represents a swing of potential of –V and at this instant the voltage at point C is -V. This results in a potential difference of 2V across the second gap and causing it to break down. This action continues across each stage gap. The first stage sphere gap, in effect, is a trigger for applying the peak voltage to the load. As part of the impulse generator, the load capacitor is large enough to overcome the effects of the stray capacitance to allow the simultaneous gap breakdowns to occur.(5)

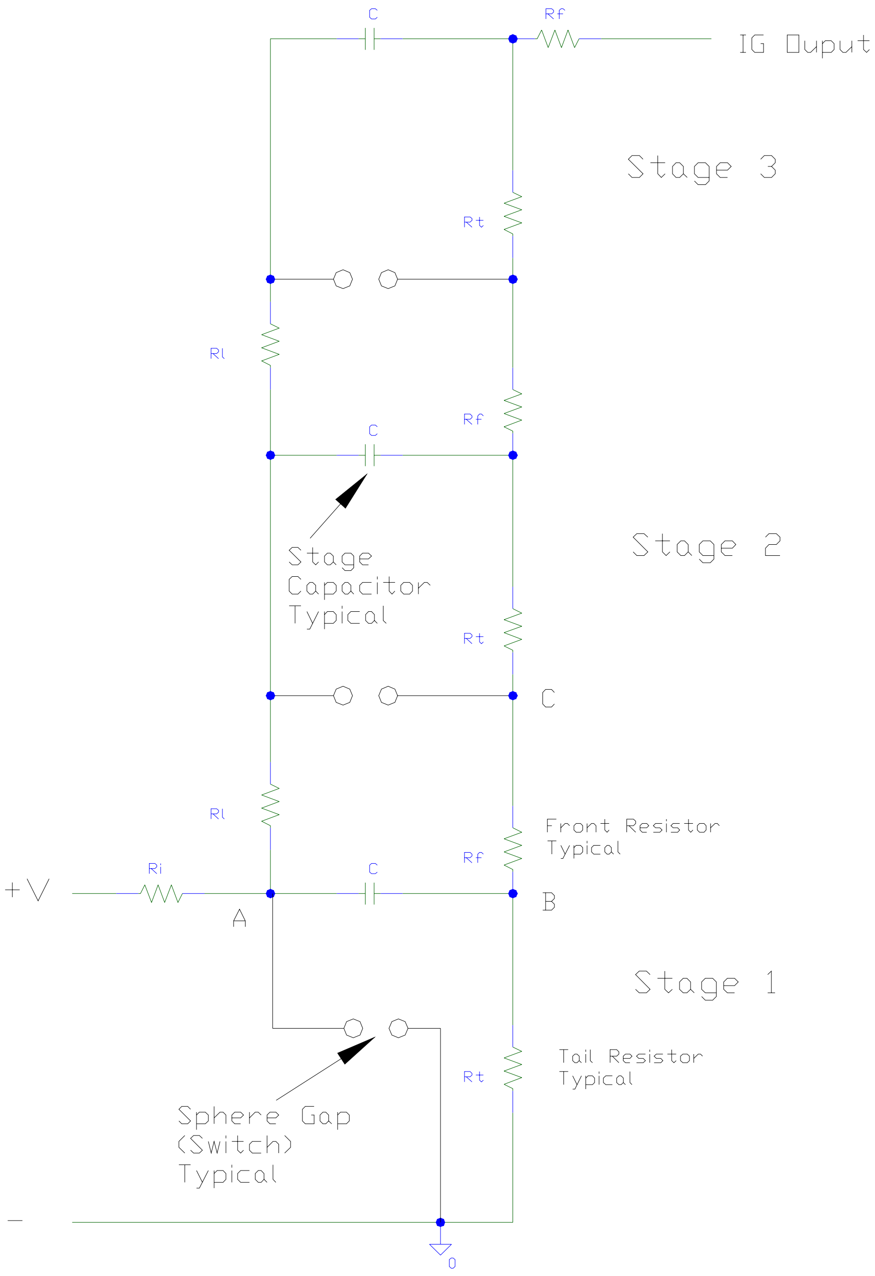

Figure 2 Impulse Generator

1.3 Impulse Generator and Equipment

The Impulse Generator used in the testing was a Hipotronics™ Series 100. It is a three-stage generator resulting in a peak capability of 300kV. The control system installed as part of the impulse generator is a Hipotronics™ model 970IG-DS, and is a programmable digital design. An impulse generator has two resistors per stage. The front resistor allows the front of the wave to reach peak in the desired time. The second resistor, referred to as the tail resistor, is required for the half-voltage level at the end or tail of the wave shape. Each stage front resistor value is 17.65Ω; the tail resistor value is 120Ω.

The oscilloscope is a Tektronix™ model TEK 544A. It is a digital oscilloscope with dual trace memory capability. The oscilloscope is connected to the voltage divider using a Tektronix 100X probe, Model P5100.

1.4 Resistive Voltage Dividers

The voltage divider is used to reduce the level of the voltage to a measurable value and generally consists of two impedances in series. The two impedances result in a fraction of the total voltage across the lower leg impedance. The lower value impedance, normally referred to as the lower leg, will have a voltage that is the input to the measurement instrument.

The experimental resistive voltage divider is a Hipotronics™ model RVD-300, rated 300kV. This divider has a high voltage resistor value of 5625Ω and a lower leg value of 75Ω. This results in a ratio of 150:1 with an output impedance to the oscilloscope of 75Ω. Refer to Figure 3 for a circuit diagram of the divider and output signal connection. It is important to match the characteristic impedance of the coaxial cable connection to the scope at both ends. This eliminates reflective traveling waves and distortion of the signal.(6) To decrease the amount of transmission line distortion, the length of coaxial cable between the divider and the scope should be kept as short as possible.

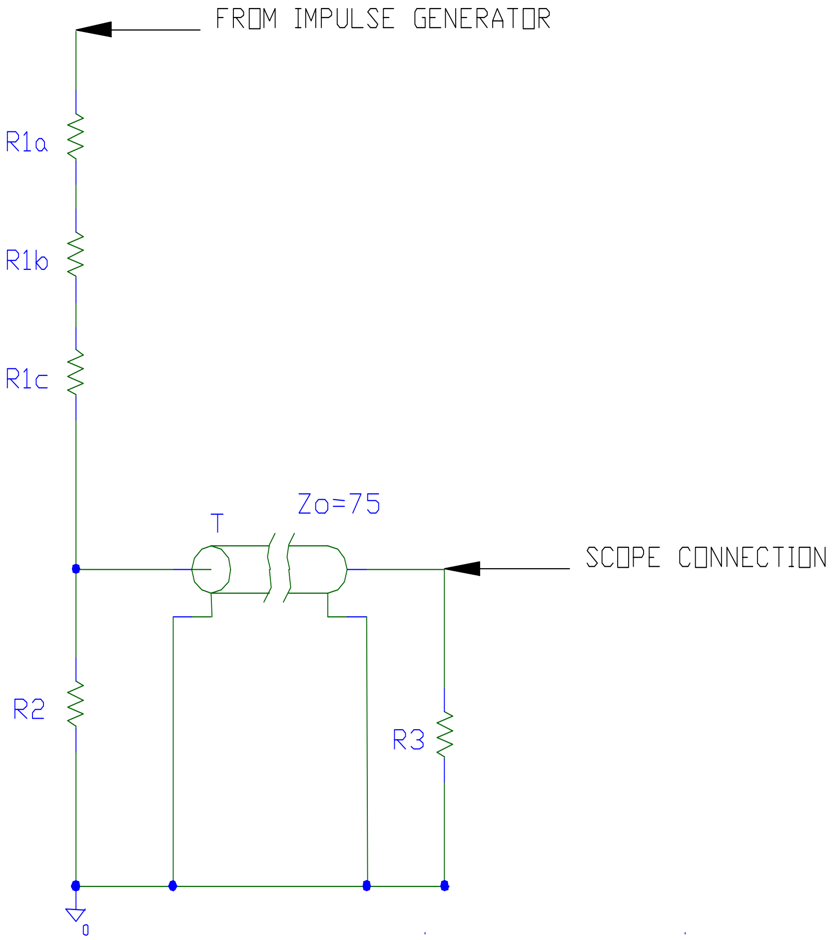

Figure 3 Voltage Divider and Oscilloscope Connection

2.0 PROPERTIES OF RESISTIVE VOLTAGE DIVIDERS

2.1 Divider Construction

The construction of a resistive voltage divider for high voltage measurements appears straightforward at first consideration. Typically, it consists of two resistances in series whose divider ratio reduces the applied value of voltage to a lower voltage value that is measured by an oscilloscope, as shown in Figure 3. Since this thesis deals with fast impulse types of voltage signals, those characteristics that result in measurement error will be addressed.

At the top of the divider is a toroidal shaped electrode that is used to alter the geometry, effectively controlling the electric field to reduce the gradient at the surface of the divider top. This toroidal electrode is normally of large diameter and is sized for the peak voltage rating of the divider.

In applications of impulse voltages, the stray capacitance of the resistor must be considered. The resistance ratio is to be constant over a wide range of frequencies during the impulse to eliminate distortion in the waveshape. The construction of the resistor is such that the inductance and capacitance are reduced to minimal levels by using wire woven into glass-fiber fabric and winding the resistor non-inductively.(7) For thermal reasons, wire is utilized to handle the high rate of energy transfer to the resistors from the generator. In this construction a capacitance exists from the high voltage arm-to-ground. A typical divider with the resistors stacked vertically has a value of capacitance-to-ground from 15 to 20pF/m of height.(8)

To reduce thermal effects, due to the energy transfer of the fast rate of rise voltage to the resistors, wire wound resistors are used rather than thin film type. The resistors are typically contained in an insulated cylinder that is filled with dielectric oil. The oil adds dielectric strength and absorbs the heat generated by repetitive impulse measurements. By reducing the thermal heating of the divider resistors, the ratio can be effectively maintained, reducing impulse signal distortion.

2.2 Calibration of Divider

The output voltage of the impulse generator is typically calibrated by using sphere gaps. The spheres are of standard dimensions. The most commonly used is a diameter of 25 cm. One of the spheres is grounded, and the other is connected to the high voltage side of the impulse generator. The relative humidity and temperature of the test cell at the time of test determines the required gap for a given voltage level. Three successive readings are made at the test level. These readings cannot vary by more than +/- three percent. Setting the gap of the spheres based on the voltage level and factors of relative humidity and laboratory temperature will produce a breakdown at a known voltage across the gap.(9) In this arrangement, the oscilloscope is utilized with the divider to record the breakdown voltage. After three readings that are within tolerance, the voltage level is typically slightly decreased for one shot. There should be no breakdown across the gap.

Although the above method is used primarily to test the ability of the impulse generator to produce the accurate desired voltage level, it also verifies the divider-to-oscilloscope measurement equipment as well.

2.3 Losses and Error

Errors and loss factors affect components in the system other than just the voltage divider. The types of errors are those involving the coaxial cable connection from the divider to the scope, electromagnetic field disturbances coupled directly to the scope, connection between generator and divider, stray ground capacitance in the divider, and the divider ratio. In this section, the error components for the entire system will be discussed.

The high voltage is reduced by the divider and transmitted to the oscilloscope via a coaxial cable connection. The cable connection is made on the low voltage arm of the divider, and this cable acts as a distributed transmission line. A traveling wave will be reflected from the end of the line if there is a difference between the characteristic impedance, Zo, and the terminating impedance. For this reason, the connections at both ends of the coaxial cable are made with an impedance that is equal to the cable characteristic impedance, Zo. Also, it has been found that the frequency-dependent transmission error can be decreased by shortening the cable connection.(10)

The electromagnetic field created by the high frequency impulse voltage generated can result in distortion of the measured CRT signal. The disturbance is noise induced into the vertical amplifier and other circuitry. To overcome this noise, the oscilloscope can be placed in a shielded enclosure that will largely eliminate the effect of high frequency fields. Commercial models of these cabinets can provide 80 to 100db field attenuation at frequencies up to 35 GHz.(11)

The lead connection from the impulse generator and the divider acts as a transmission line with distributed parameters. At high frequencies, the lead's stray capacitance and residual inductance have an effect. The result of this inductance and capacitance-to-ground causes a phase shift in the current relative to voltage. This phase shift results in distortion between the source and the test sample. The lead impedance changes along its length so that the current reduces slightly by this change. To minimize the inductance of this lead connection, wide flat copper tape is used, and the actual connection is kept as short as possible.

For impulse testing, the stray capacitance to ground of the resistive voltage divider is a consideration. The high voltage is applied to the top of the divider and the stray capacitance is distributed along the length of the resistor stack. The current flow through the resistor will vary as it moves down the resistor stack. One important quality factor for impulse voltage measurement is the divider time constant, τ, in response to a step input.

$$\tau = (R \times Ct)/6 \qquad (2\text{-}1)$$

Ct represents the total capacitance to ground of the divider. A typical value for total capacitance, Ct, is 15 to 20pF/m in length.(12) For a 1.2μs rise-to-peak voltage impulse wave the time constant, τ, should be ~200ns or less for accurate measurement. The divider resistance (R), from Equation (2-1), should be small enough to allow accurate response to the fast impulse wave. Solving Equation (2-1) for R gives:

$$R=6 \times (\tau/Ct) \qquad (2\text{-}2)$$

By substituting for $Ct = 20pF/L$ and $\tau = 200ns$ a value of R can be derived as follows.

$$R \leq 60000/L \qquad (2\text{-}3)$$

Where L is the length of the voltage divider.

The divider ratio should remain constant through the duration of the entire impulse wave. Any change in the ratio will affect the shape of the impulse wave. As the energy is transferred across the divider, the heating of the resistors can change the resistive value. The resistor construction is usually wound wire, and the divider enclosure is filled with transformer oil. The transformer oil absorbs the heat generated in the resistors and maintains the resistor ratio.

2.4 Connection to Oscilloscope

The cable connection should be terminated at both ends with impedance equal to the characteristic impedance, Zo, of the cable. By doing this, the cable is the same as a resistive voltage divider. Refer to the Figure 3 for the circuit diagram of a connection to a voltage divider.

The resistive voltage divider employs a lower leg resistor of 75 ohms, which is equal to the characteristic impedance of the coaxial cable. Likewise, the connection at the oscilloscope internally represents an impedance of 75 ohms. In Figure 3 Zo=R2=R3=75 ohms.

Probes are available to coordinate with the oscilloscope to provide further ratio reduction in the measured voltage from the divider. The most commonly used ratios are 100X or 1000X, depending upon the desired test voltage level of the impulse generator. These probes, when connected to the oscilloscope by a pinning arrangement internal to the probe connector, set the scope scaling automatically.

3.0 STATEMENT OF THE PROBLEM

The problem to be solved in this Thesis is to create a simulation circuit that has an output wave shape equivalent to that of an Impulse Generator (IG). An existing 300kV Impulse Generator at the Cutler-Hammer Technology Center will be utilized to generate the laboratory testing results. Several different voltage levels will be tested and curves plotted from the laboratory equipment setup. The Impulse Generator setup is utilized for impulse testing of Medium Voltage Switchgear up to and including 250kV levels. The testing wave shape is 1.2 x 50μs, with the peak voltage reached in 1.2μs. The quality parameters for calibration of the Impulse Generator as defined by IEEE Standard 4 will be used for this study.

Using the IG set, several plots will be generated from the oscilloscope readings. The plotted wave shapes will be used as a base to establish the required output for the SPICE simulation circuit. The plotted oscilloscope output includes the effects of the inherent stray capacitance of the divider. Values of stray capacitance will be added to the simulation circuit to match the plotted curve. The divider will be analyzed and the turn-to-turn and turn-to-ground capacitance will be examined in detail. The effect of heating on the actual resistive value of the divider and the resulting change in output signal using the simulation will be examined.

The actual IG performance can include a certain amount of error in the output wave shape. This error is not present in a simulation circuit. A standard, IEEE 4, has been developed to account for the allowable amount of error and is noted in this Thesis.

Several iterations may be required to tune the value of stray capacitance in the simulation to more closely match the IG generated wave shape. Also, the value for the initial charge on the stage capacitors is the same as that used in the actual impulse generator. These final simulation values will be compared with the base wave shape details.

4.0 EXPERIMENTAL TESTING

4.1 Testing Setup

The equipment used for the experimental testing was discussed in Section 1.3. This equipment is used to perform design impulse testing of breakers and assemblies rated up to and including 38kV. Calibrated instruments in the laboratory provide the humidity and temperature at the time of testing. A test specimen was not used for this demonstration. The voltage divider with a load capacitor was connected to the output of the impulse generator, and the measurement 100x Probe was connected to the oscilloscope.

4.2 Calibration

Testing was performed on September 14th, 2001 at the Cutler-Hammer Technology & Quality Center in Pittsburgh. The multiplication factor for the various impulse levels has been documented by calibration performed in October of 2000; see Table 1. The kV multiplication factor (Kd) was used to multiply the actual oscilloscope measured value (Vo) to arrive at the impulse peak kV value, see Equation (4-1).

$$\text{Vpeak} = \text{Vo} \times \text{Kd} \qquad (4\text{-}1)$$

The conditions recorded at the time of testing were recorded on the test form (see Appendices A1, A2 and A3). To calculate the correction factor, use 0.3855 x Pressure / Temperature, where Temperature is in °K and Pressure as mm hg. A typical correction factor for the 62kV testing is 0.3855 x 765.81 / 301.15 = 0.980. The value of the correction factor for each voltage tested was recorded on the test forms themselves.

The scope reading, actual, was multiplied by the scope kV/V value and recorded as the measured Peak kV. For example, a 62 kV test with an actual scope reading of 444 is multiplied by 140.14, for a positive wave, and is 62222.16 V. The corrected Peak is derived by dividing the measured value by the correction factor and in this example is 63.492 kV.

Table 1 System Calibration with Oscilloscope

Impulse Level Setting kV	Polarity	Measured voltage average (Vo) V	Average Scale Factor, (Kd) V/V	Actual Impulse Level (Vo x Kd) kV
62	Positive	433.4	140.14	60.74
62	Negative	433.4	141.63	61.38
75	Positive	511.27	145.37	74.32
75	Negative	494.18	150.4	74.32
95	Positive	634.54	148.07	93.96
95	Negative	616.4	152.42	93.95
125	Positive	828	149.3	123.62
125	Negative	806.4	153.3	123.62
150	Positive	989.8	149.57	148.04
150	Negative	976	151.69	148.05
170	Positive	1109	150.38	166.77
170	Negative	1101	150.86	166.10
200	Positive	1319	148.59	195.99
200	Negative	1328	147.59	196.00

The calibration of the front of wave time to peak (T1), per IEEE Standard 4, is T1 = 1.67 x T. The value, T, is defined as the amount of time for the voltage to go from 30 percent to 90 percent of peak level, see Figure 1. A line is drawn between these points on the wave curve and where this line intersects the zero voltage axis represents the start of time (T1). The actual measured calibration time (T) of the impulse generator was found to be 0.752μs for positive polarity and 0.712μs for negative polarity.

$$T1 = 1.67 \times 0.752 = 1.25\mu s \text{ (positive polarity)}$$

$$T1 = 1.67 \times 0.712 = 1.19\mu s \text{ (negative polarity)}$$

The allowable tolerance, per IEEE, for T1 (Figure 1) is between 0.84 and 1.4μs. The above times show that the impulse generator is well within tolerance for front of wave time to peak voltage.

The tail of the impulse wave time (T2), see Figure 1, is determined by plotting the wave and finding the time at which the voltage is one-half of the peak voltage. Per IEEE Standard 4 this time should be between 40 and 60μs. From the calibration record the following is the T2 time for the impulse generator.

T2 = 44.5μs (positive polarity)

T2 = 58.2μs (negative polarity)

From the above values it is shown that the impulse generator tail of the wave shape is also in calibration.

4.3 Response Time and Stray Capacitance

As previously discussed, the typical value of stray capacitance-to-ground, Ct, of a resistive voltage divider is in the order of 15 – 20 pf/m. The Hipotronics™ RVD-300 voltage divider has a length 1.04m . The Ct for this device is approximated as 20 pf/m x 1.04m = 20.8 pf. The response time, τ, is equal to R x Ct / 6 and substituting for R as 5625Ω and Ct of 20.8 pf yields a value of τ = 19.5ns. This value of 19.5ns for a 1.2x50μs wave is an acceptable response time.

4.4 Test Levels Selected

Three levels were selected for testing. The levels were 62, 75 and 95 kV. A 1.2 x 50µs wave was used for all three voltage levels. All three of these levels had previously been calibrated for this test setup. At each of the kV levels, three positive and three negative waveshape impulses were tested and recorded.

Refer to the Appendix for the test result forms. All of these test wave shapes have been captured, and samples for each are enclosed in this document; see Figures 4, 5, 6, 7, 8 and 9.

5.0 EXPERIMENTAL RESULTS

5.1 Voltages Tested

Voltage levels were picked from the impulse generator previously calibrated levels. The actual test values used were 62.5, 75 and 95kV BIL. As previously stated, these levels had been calibrated by Dr. Roy Voshall, of Gannon University. The calibrated voltage levels for this equipment ranged from 62 kV to 200 kV.

5.2 Discussion of Results

For each voltage test level, three negative and three positive impulse tests were conducted. The correction factors were calculated for negative and positive impulses, based on multipliers from the calibration. The correction factors, atmospheric readings and multipliers for each test level are shown in Table 2.

Table 2 Correction Factor

kV Test	Pressure (mm hg)	Temperature Deg. K	+ Impulse Multiplier	- Impulse Multiplier	Correction Factor
62.5	765.81	301.15	140.14	141.63	0.98
75		301.65	145.37	150.4	0.979
95		301.65	148.07	152.42	0.979

Refer to test sheets 1, 2 and 3 enclosed, in the Appendix, for actual values recorded during testing. For each impulse test a measured and corrected value was recorded on the test sheet form. The charging kV level was also recorded and was taken from the Hipotronics™ 970 control display. This value was not used in any of the calculations and is not typically calibrated. The display is generally used as a reference to initially set up the test. From the 970 control, the kV value can be raised or lowered. This actually increases or decreases the gap on each stage.

Table 3 is the collection of the positive and negative measured test values for each of the kV test levels. The three impulse tests for each, polarity, have been averaged in the table for discussion purposes.

Table 3 Test Results

kV Test Level	(+ or -)	Measured kV	Corrected kV
62.5	+	62.2	63.5
	+	62.2	63.5
	+	61.9	63.2
	Avg. +	62.1	63.4
	-	61.2	62.4
	-	61.2	62.4
	-	61.5	62.7
	Avg. -	61.3	62.5
75	+	79.1	80.8
	+	79.1	80.8
	+	79.1	80.8
	Avg. +	79.1	80.8
	-	78.8	80.5
	-	78.8	80.5
	-	79.4	81.1
	Avg. -	79	80.7
95	+	91.2	93.2
	+	91.8	93.8
	+	91.8	93.8
	Avg. +	91.6	93.6
	-	91.4	93.4
	-	92.7	94.6
	-	92.1	94
	Avg. -	92.07	94

All of the test oscillographs were captured digitally. Samples of each positive and negative wave have been included in this document, see Figures 4, 5, 6, 7, 8 and 9.

Because of the atmospheric effects, the losses, and the other factors already discussed, the actual voltage generated varies from that measured. The testing standard, IEEE 4, outlines the allowable tolerance for impulse testing. The rise time to peak is controlled by the pre-load capacitor and the value of the front resistor. The tail resistor controls the fall of the wave shape to 50 percent of peak value in a specified time.

The experimental impulse testing was conducted first at 62.5kV, then 75kV, and finally at 95kV with a total of six impulse tests at each voltage level. After examination of the test data sheets, no noticeable change due to heating, or the voltage divider, can be observed. The typical laboratory procedure allows for two minutes between impulse tests, which reduces thermal effects to the divider ratio.

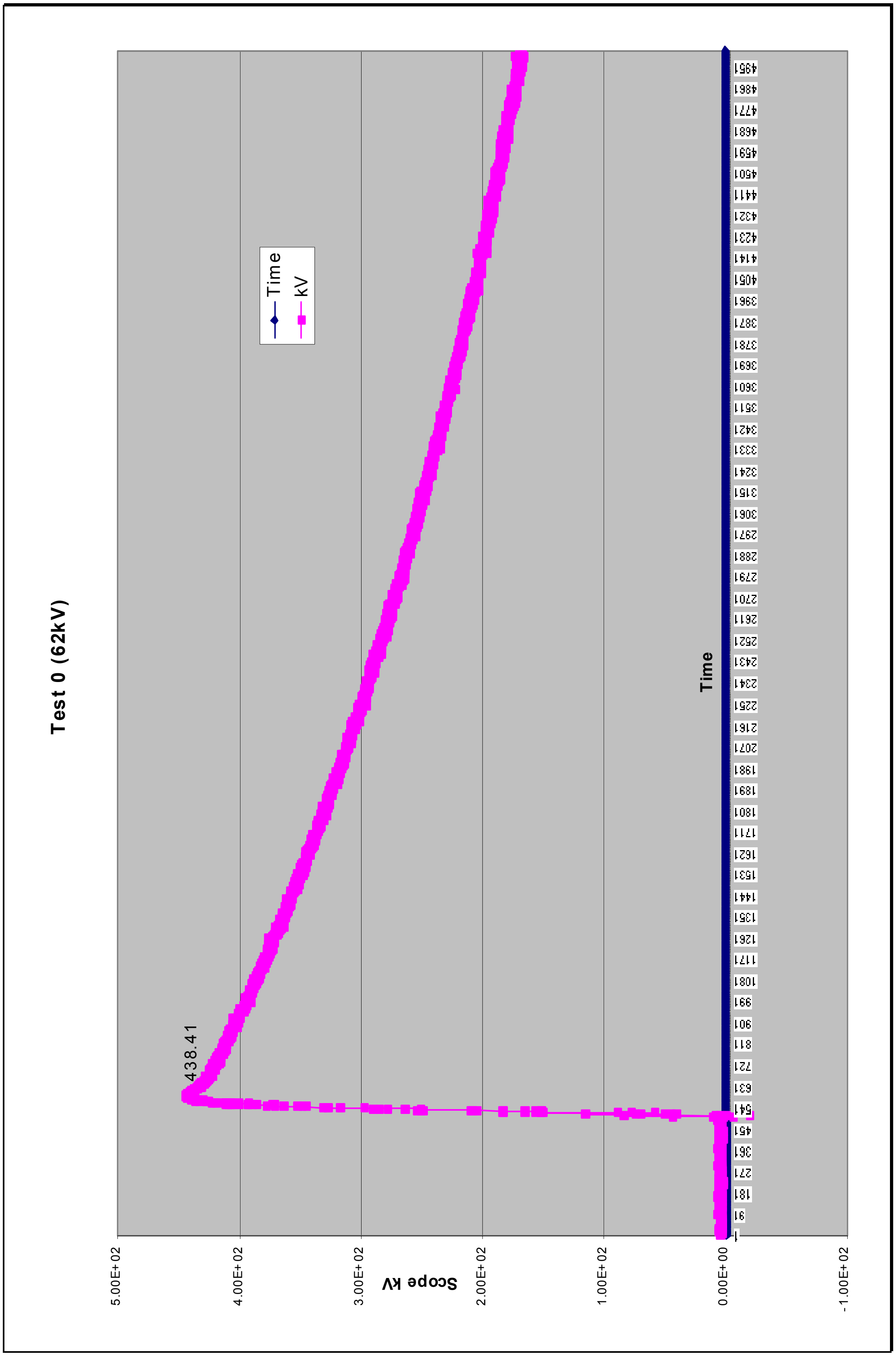

Figure 4 Test 0 Positive 62kV Test Wave

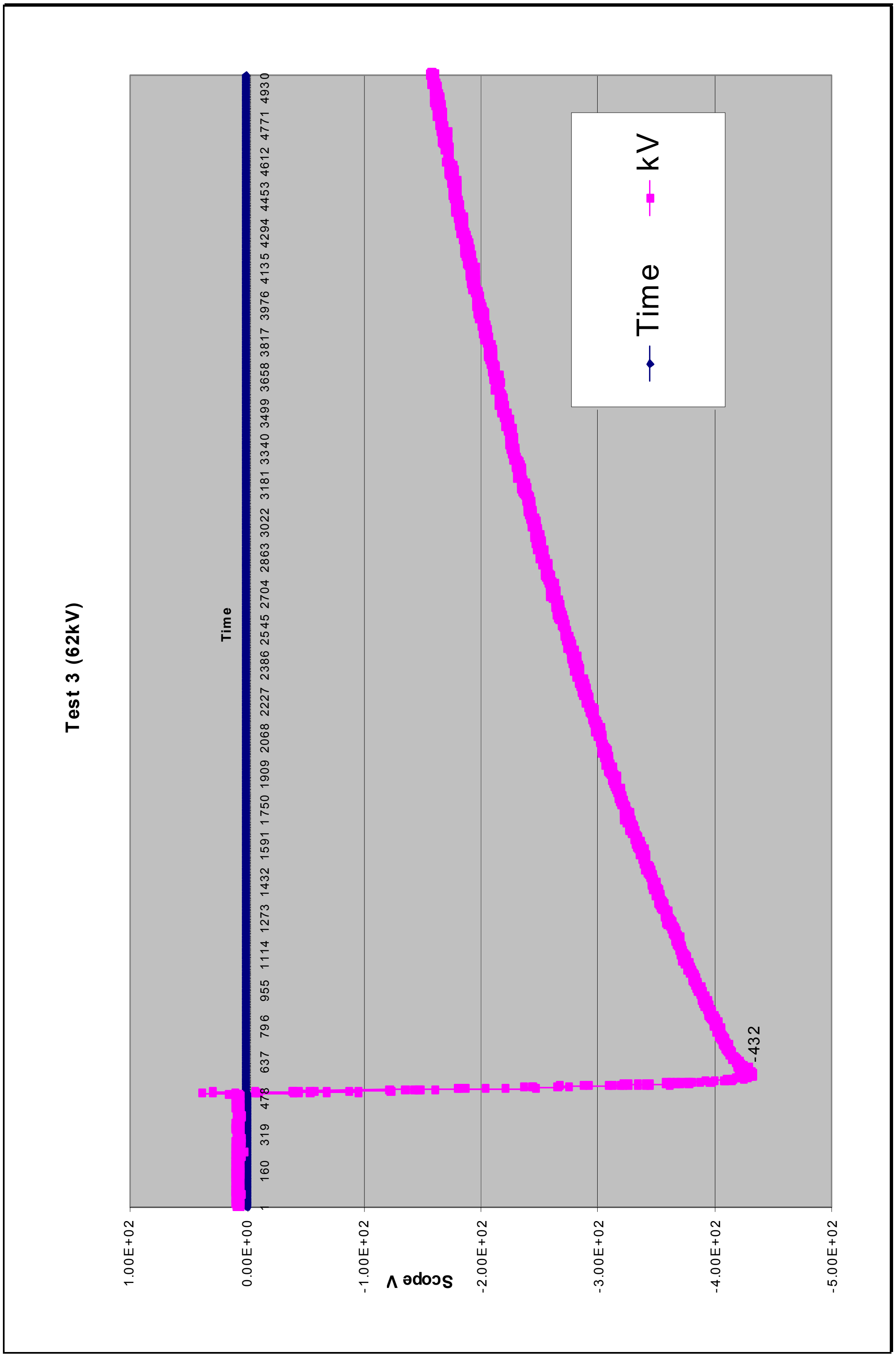

Figure 5 Test 3 Negative 62kV Test Wave

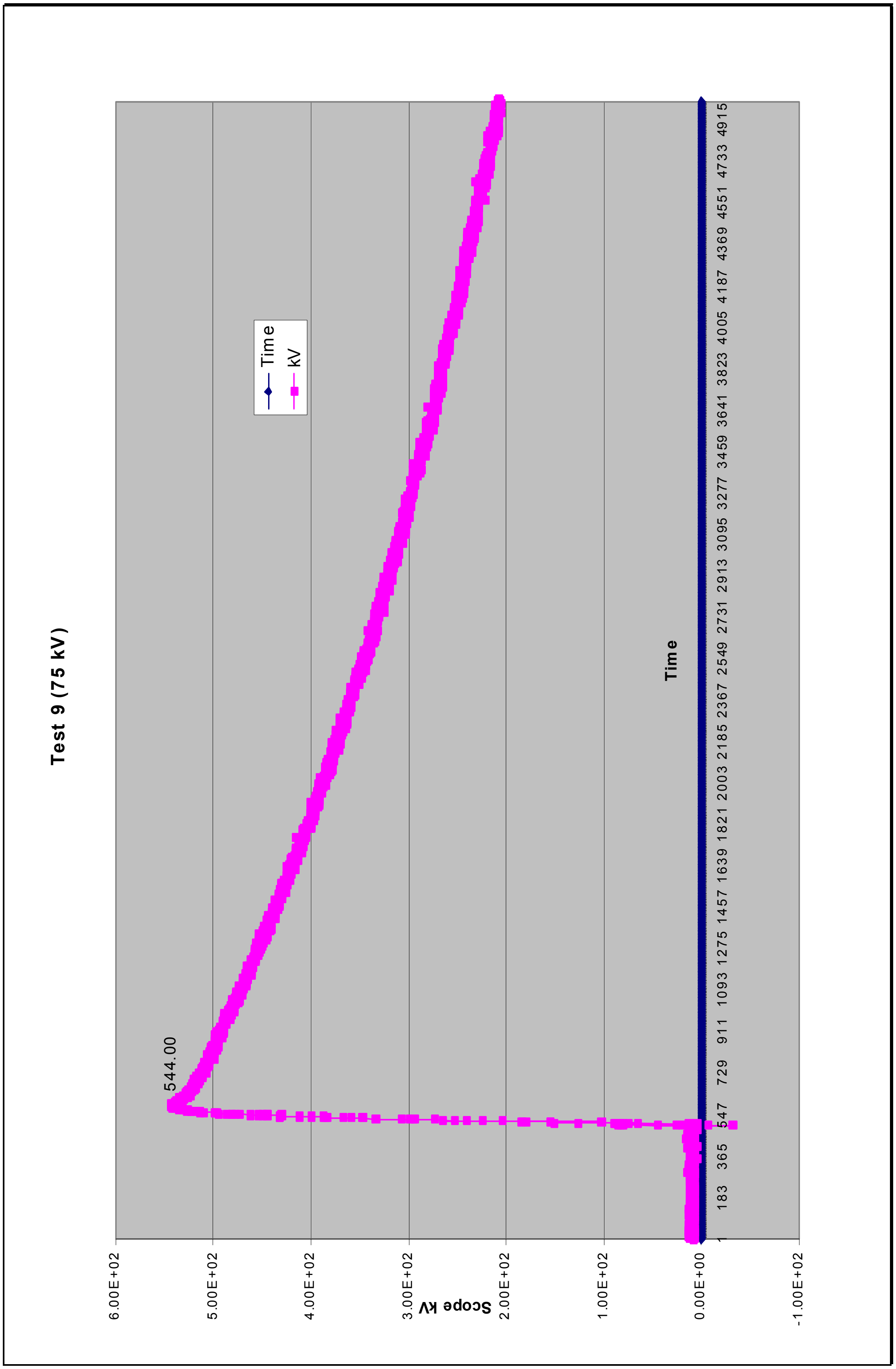

Figure 6 Test 9 Positive 75kV Test Wave

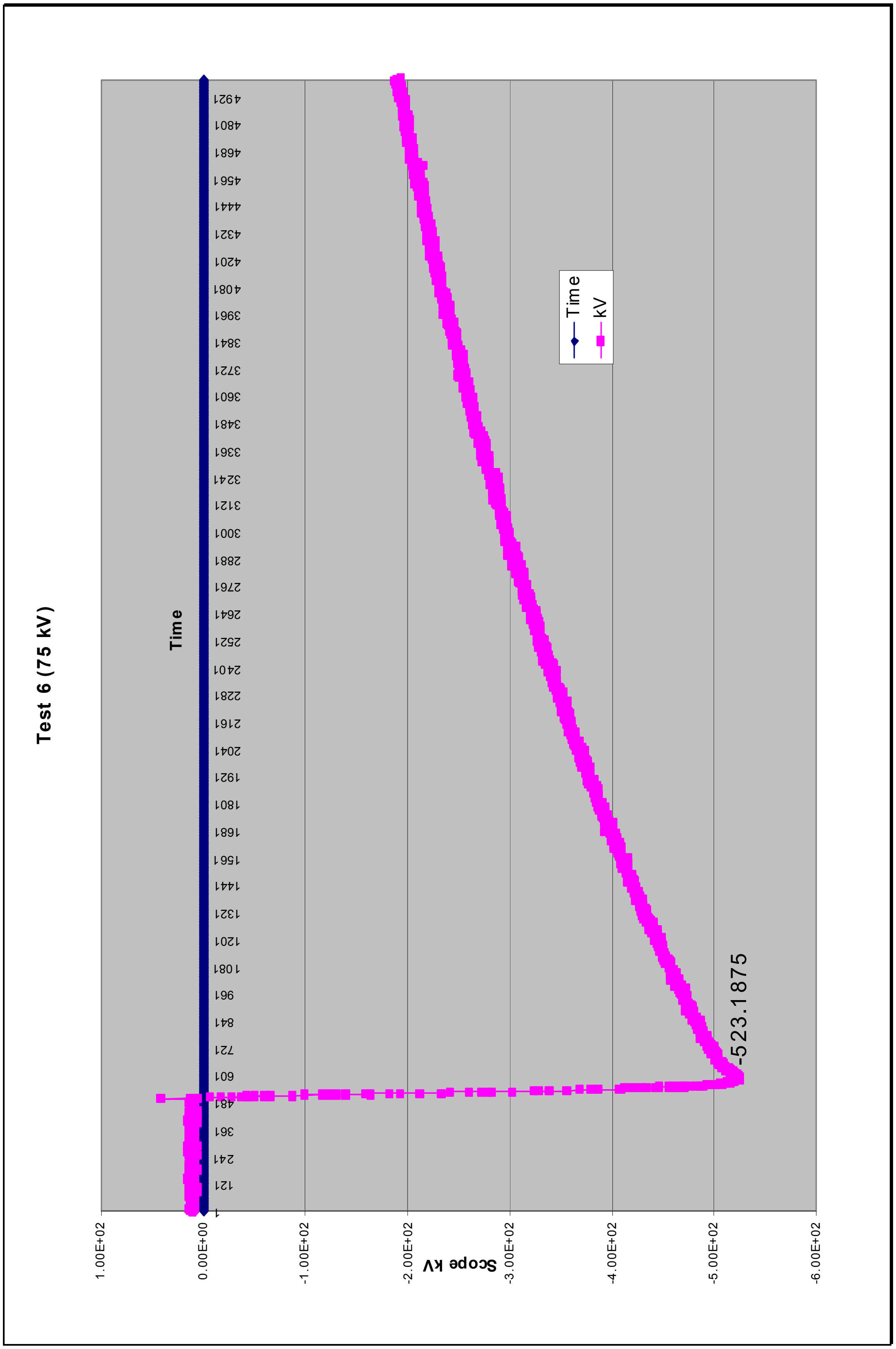

Figure 7 Test 6 Negative 75kV Test Wave

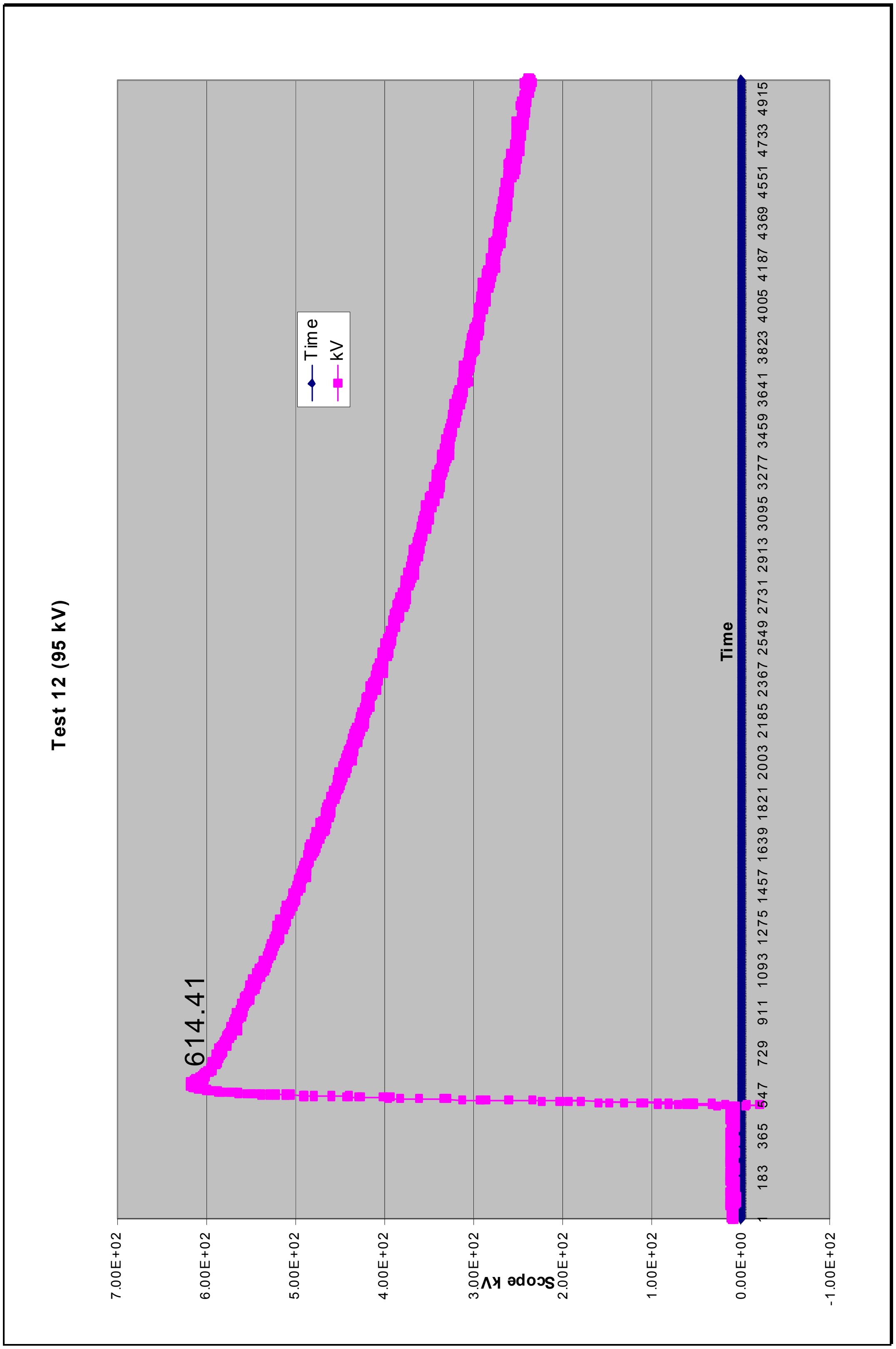

Figure 8 Test 12 Positive 95kV Test Wave

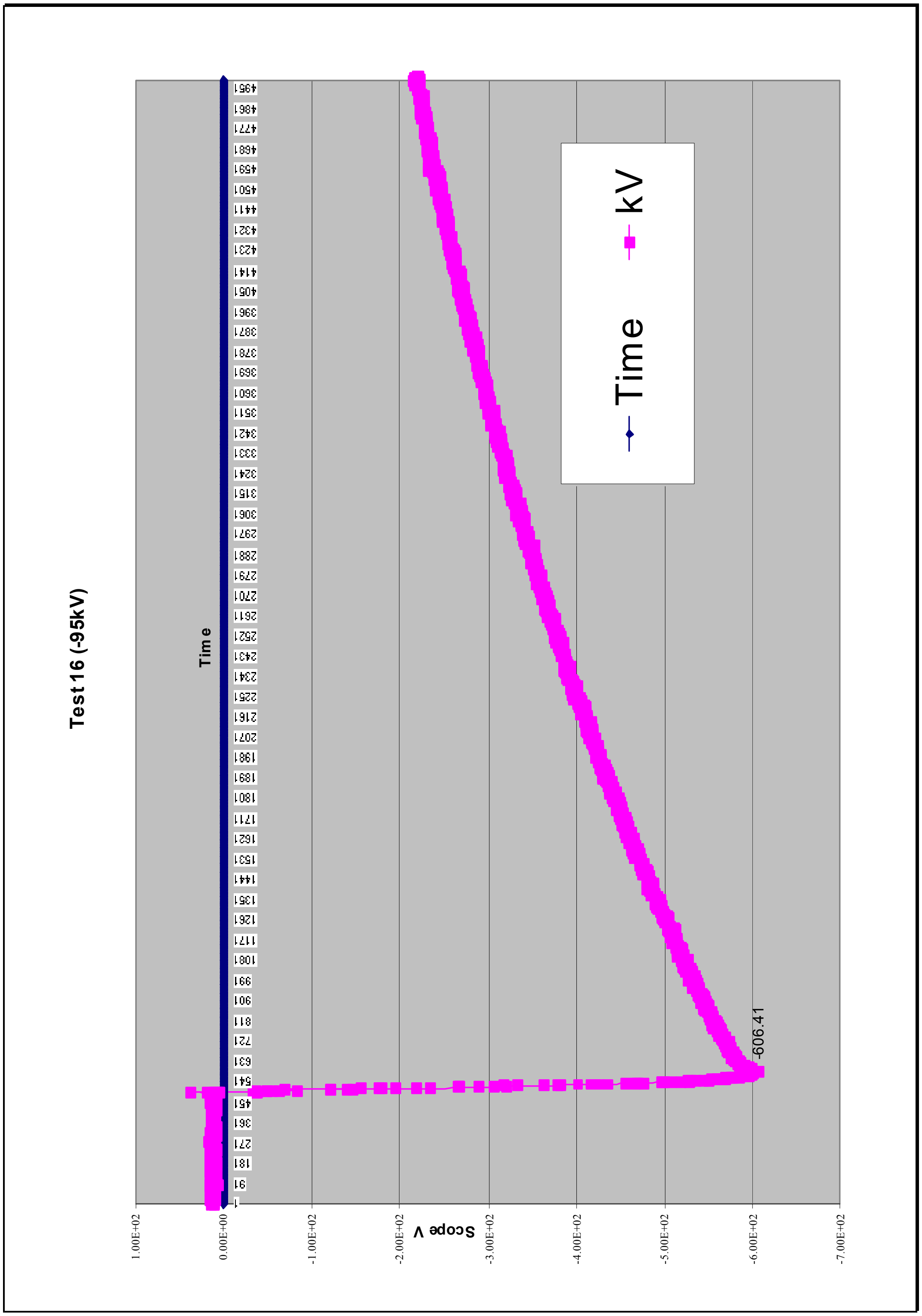

Figure 9 Test 16 Negative 95kV Test Wave

6.0 SPICE SIMULATION

6.1 The SPICE Circuit

The three-stage impulse generator was simulated using SPICE™ software. The schematic of the simulated generator is shown in Figure 10. The stage sphere gaps were simulated by the use of switches, as shown. The output of the generator was also switched, and all four switches were closed at the same time. Each of the three stage capacitors were given an initial charge voltage value, which is equal to 1/3 of the total kV test voltage. The values of front and tail resistors, as well as the stage capacitors, are the same as used in the actual impulse generator.

Figure 11 is a sample of a 62.5kV simulation output using the circuit from Figure 10. The time to peak is 1.175µs with a peak voltage of 66.72kV. The peak voltage level is higher than desired from this simulation circuit. The tail of wave time (T2), 50 percent of the peak voltage, was approximately 45µs. To more closely match the base laboratory circuit, stray capacitance will be added to Figure 10 SPICE model.

In order to apply stray capacitance to the voltage divider the circuit would require modification. The stray capacitance was previously estimated to be 20.8pF, based on 20pF per meter in length of the voltage divider. This value of capacitance was then inserted in the middle of the voltage dividers' high voltage resistor leg. The total resistance of the voltage divider multi-element high voltage leg was evenly divided into two resistances connected in series. The stray capacitor was then connected between these two resistors.

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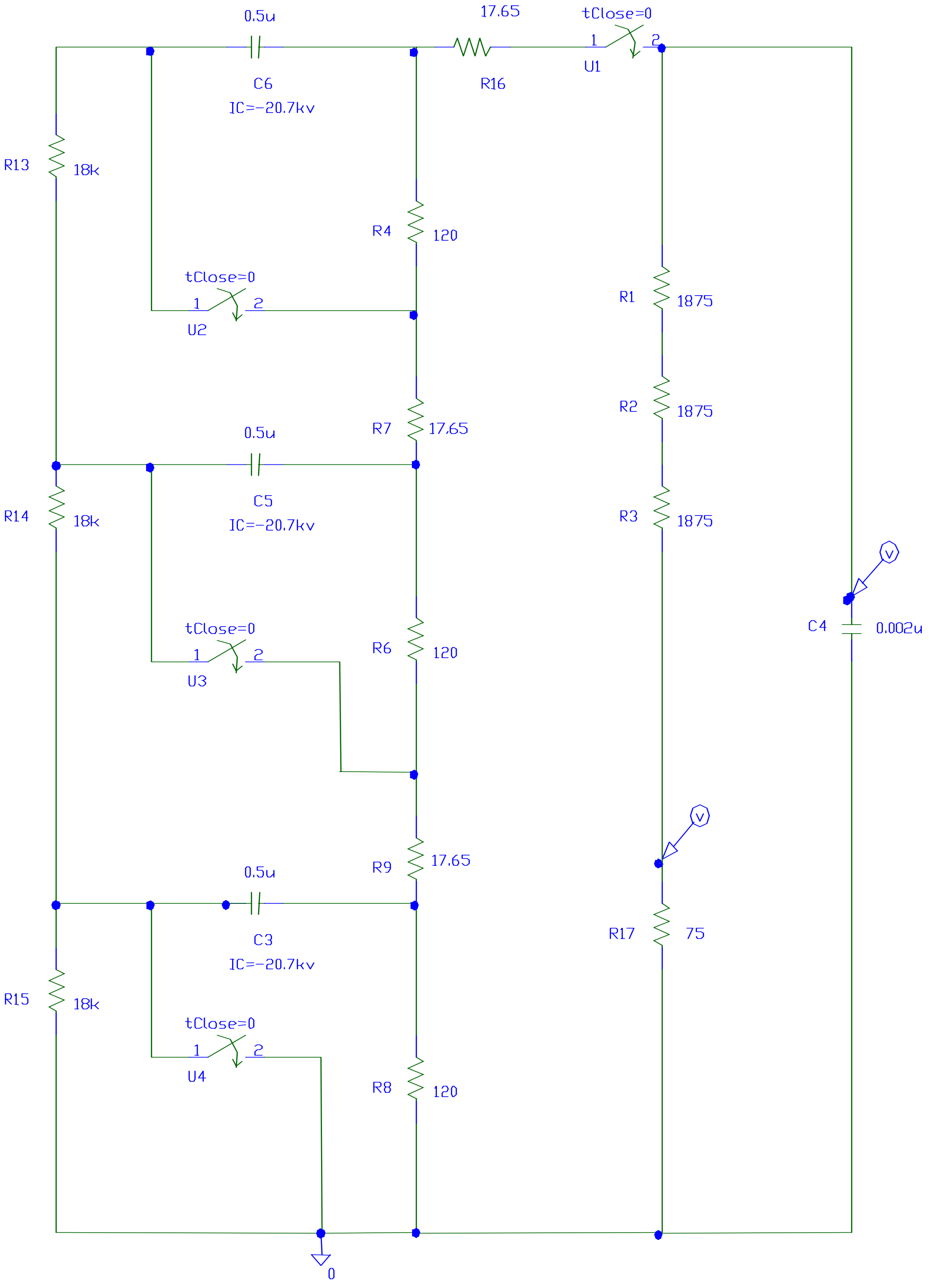

Figure 10 SPICE Simulation Schematic

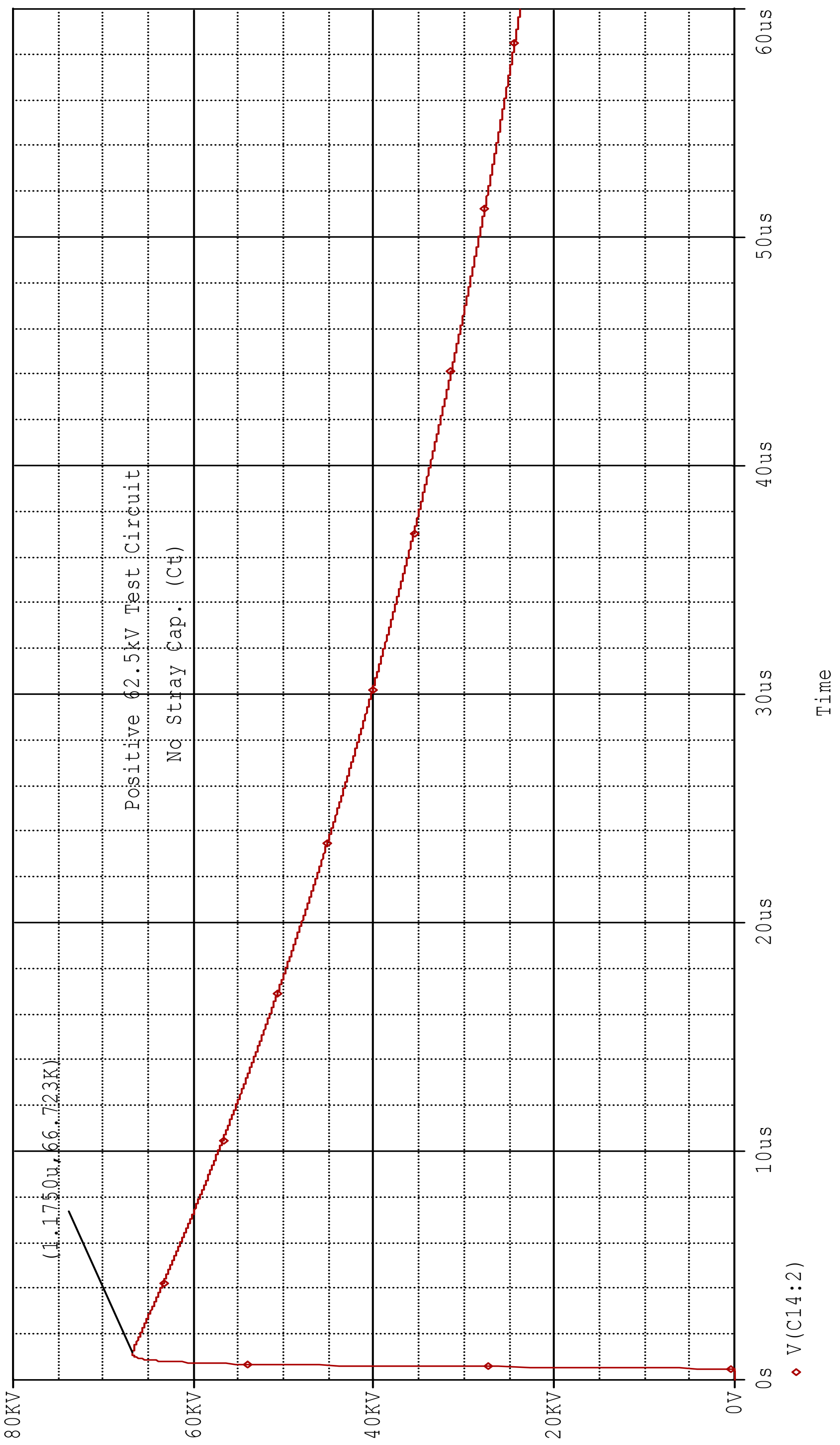

Figure 11 SPICE Output Wave (Stray Capacitance (Ct) not included)

The initial simulation output wave, using a stray capacitance value of 20.8 pF, resulted in a nearly negligible change in the wave shape. The peak voltage was higher than the base test wave value of 63.4kV for a positive 62.5 kV impulse test. The desired peak voltage level for the simulation is to be as close as possible to the base 63.4kV peak value. It is apparent that a larger value of capacitance would be required to reduce the output wave peak voltage and more closely match the T1 time to peak.

After closer examination of the SPICE simulation circuit, Figure 10, stray capacitance would also be added to each stage tail resistor. The tail resistors are shorter in length than the voltage divider and would have a smaller value of stray capacitance. Figure 12 shows the simulation circuit with stray capacitance added to both the voltage divider and tail resistors.

Figure 12 is the second simulation circuit that has been used for this study. In this circuit the stray capacitance, Ct, has been inserted. The values of stage and stray divider capacitances were then varied, one at a time, each time evaluating the output wave. Using a trial and error type of process the suitable values of stage and stray divider capacitances were found. The final capacitance values are those shown in the Figure 12 circuit. The values are 300pF for each stage and 2000pF for the divider stray capacitance.

Figure 13 shows a comparison of the front of wave for the simulation circuits with and without the stray capacitance (Ct). The front of wave time (T1) is 1.23μs and nearly matches the base positive front of wave time as 1.22μs. The stray capacitance also lowers the value of peak voltage to more closely match the actual test value.

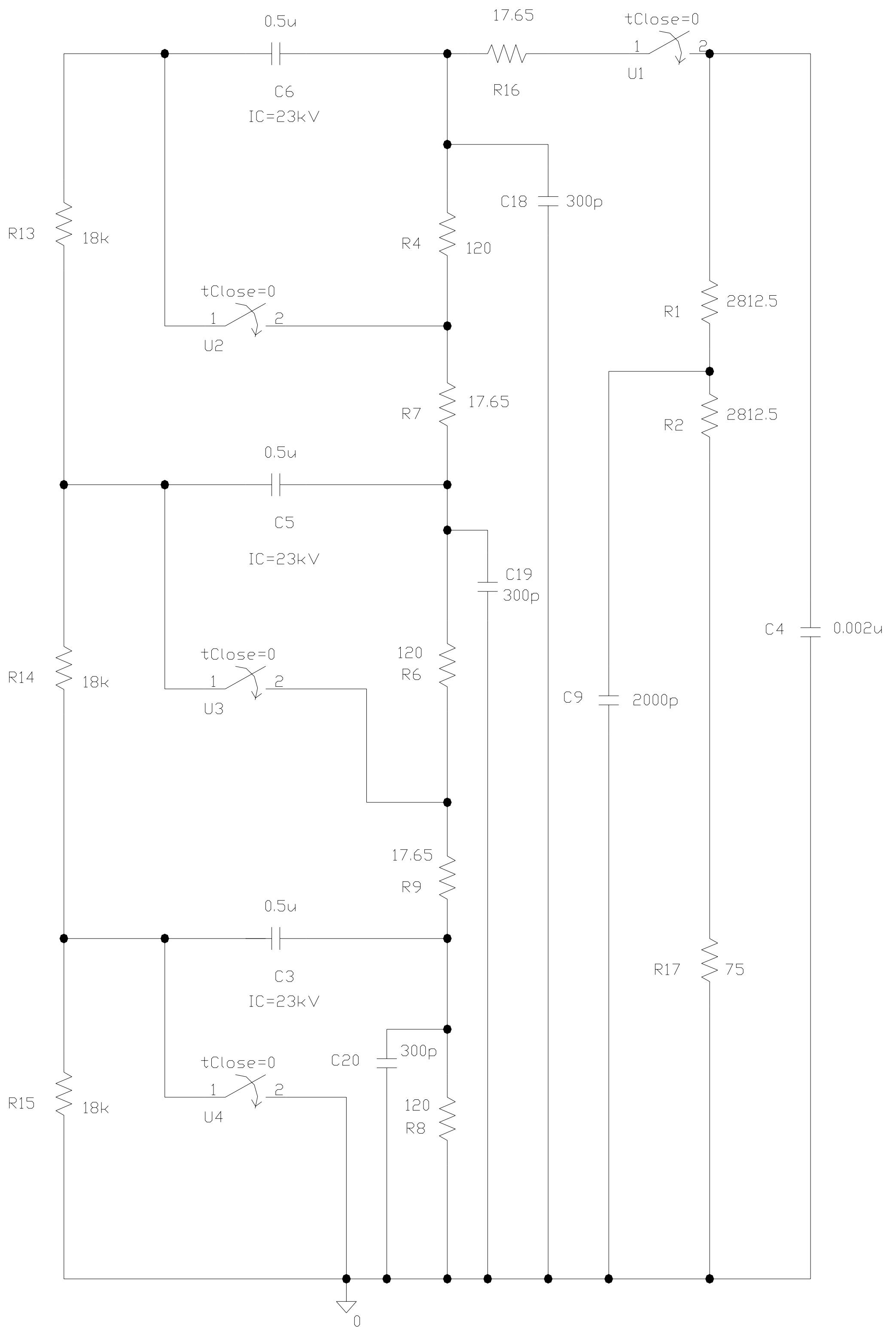

Figure 12 SPICE Circuit with Ct (stray capacitance)

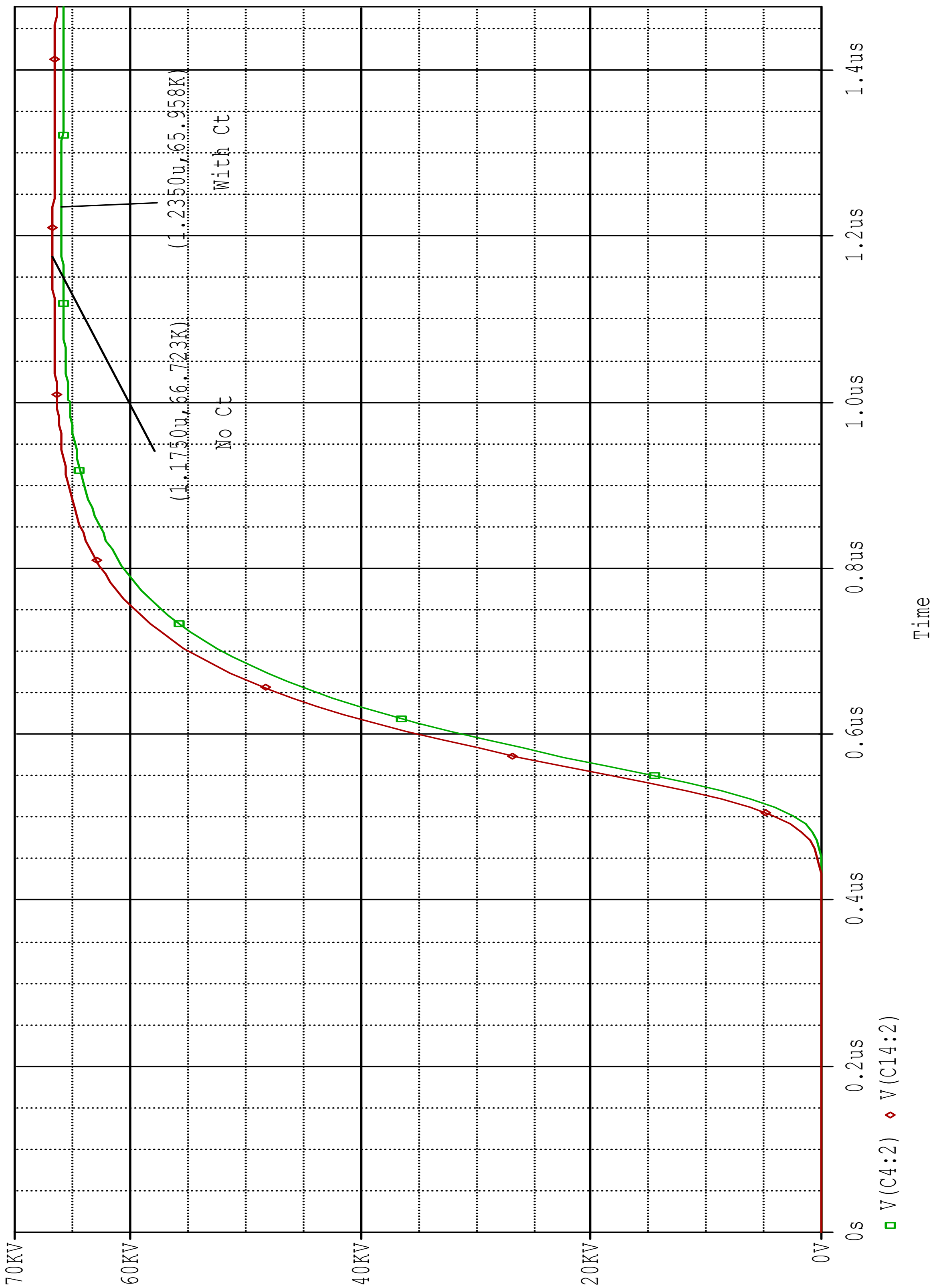

Figure 13 SPICE 62kV Front of Wave, with and without Ct.

A negative or positive wave shape can be achieved by setting the initial condition of each stage capacitor as positive or negative. The simulation results are shown in Table 4. For the simulation circuit the positive and negative impulse waves are identical in peak voltage, time to peak and wave duration. The charge or initial condition for each stage capacitor was set equal to that used in the actual impulse generator.

Table 4 Simulation Results

Charge	kV
23 kV	65.9
	-65.9
28 kV	80.3
	-80.3
32 kV	91.8
	-91.8

The three test voltage levels were run in the simulation and the results are shown in Figures 14, 15, 16, 17, 18 and 19. It is seen from the results that the front of wave time to peak voltage (T1) is exactly the same for all voltage levels. This is a result of using the same stray capacitance values in the simulation circuit. By changing the initial condition voltage of the stage capacitors the test voltage levels could be simulated, much the same as in an actual impulse generator.

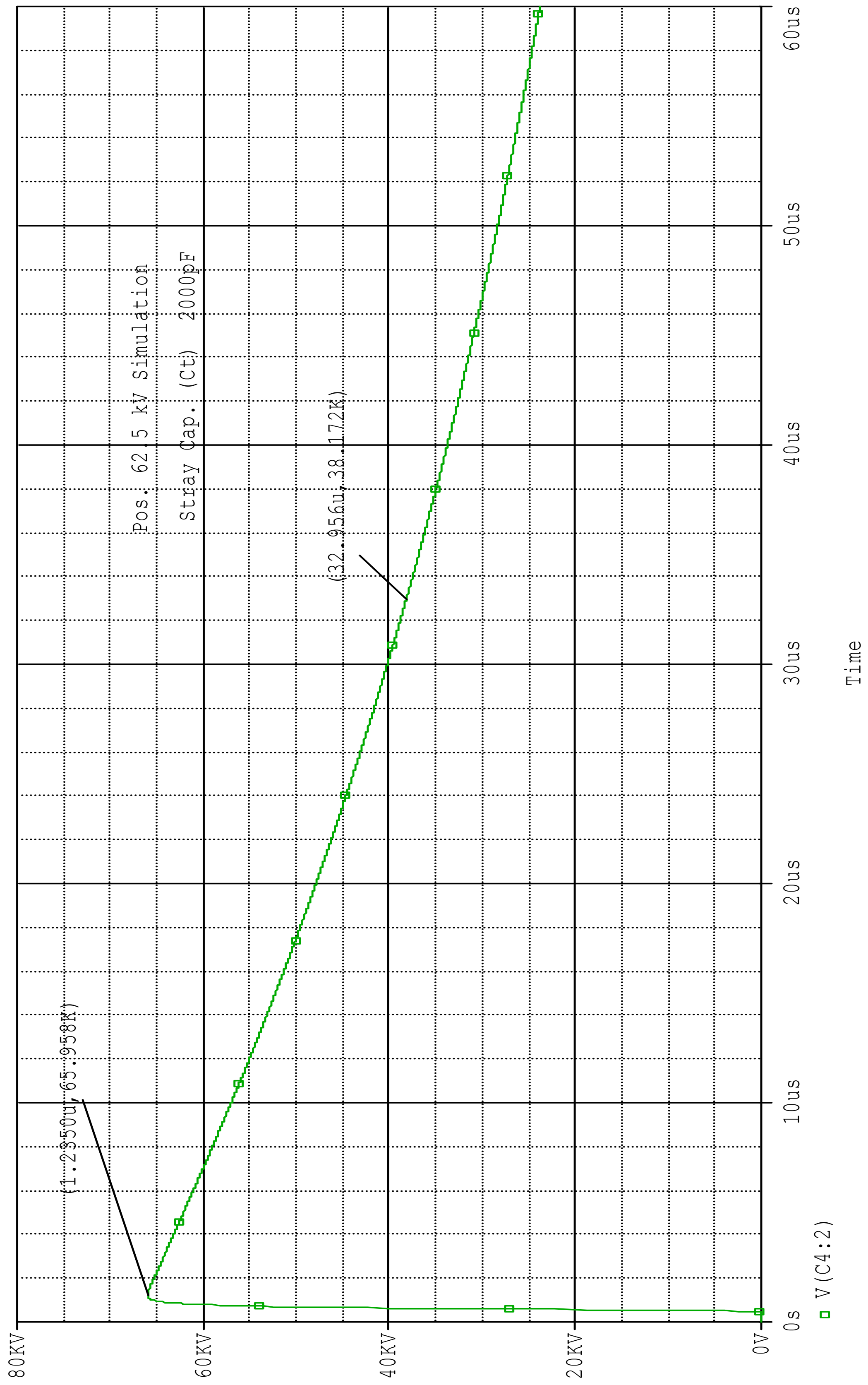

Figure 14 62.5kV Positive SPICE Simulation

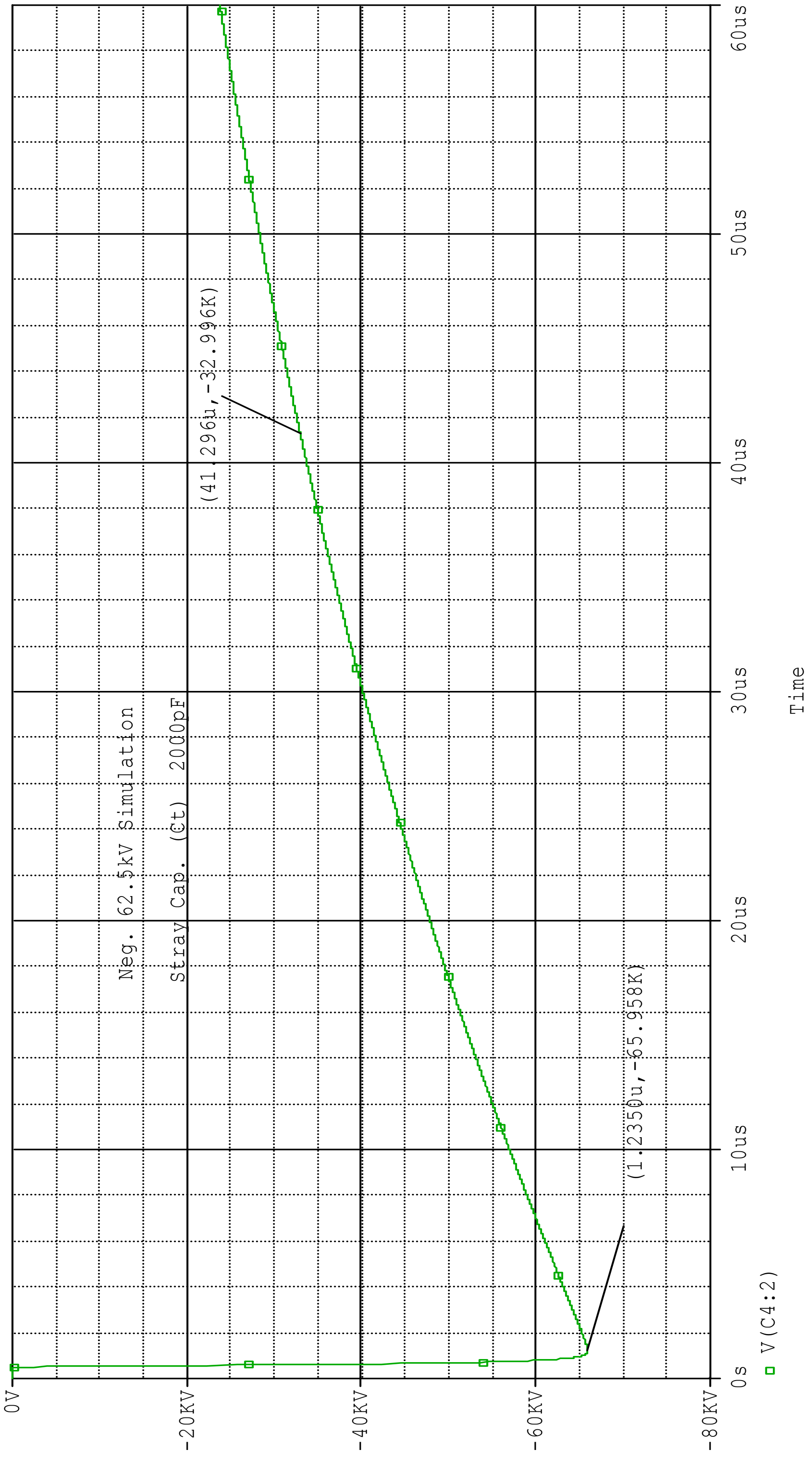

Figure 15 62.5kV Negative SPICE Simulation.

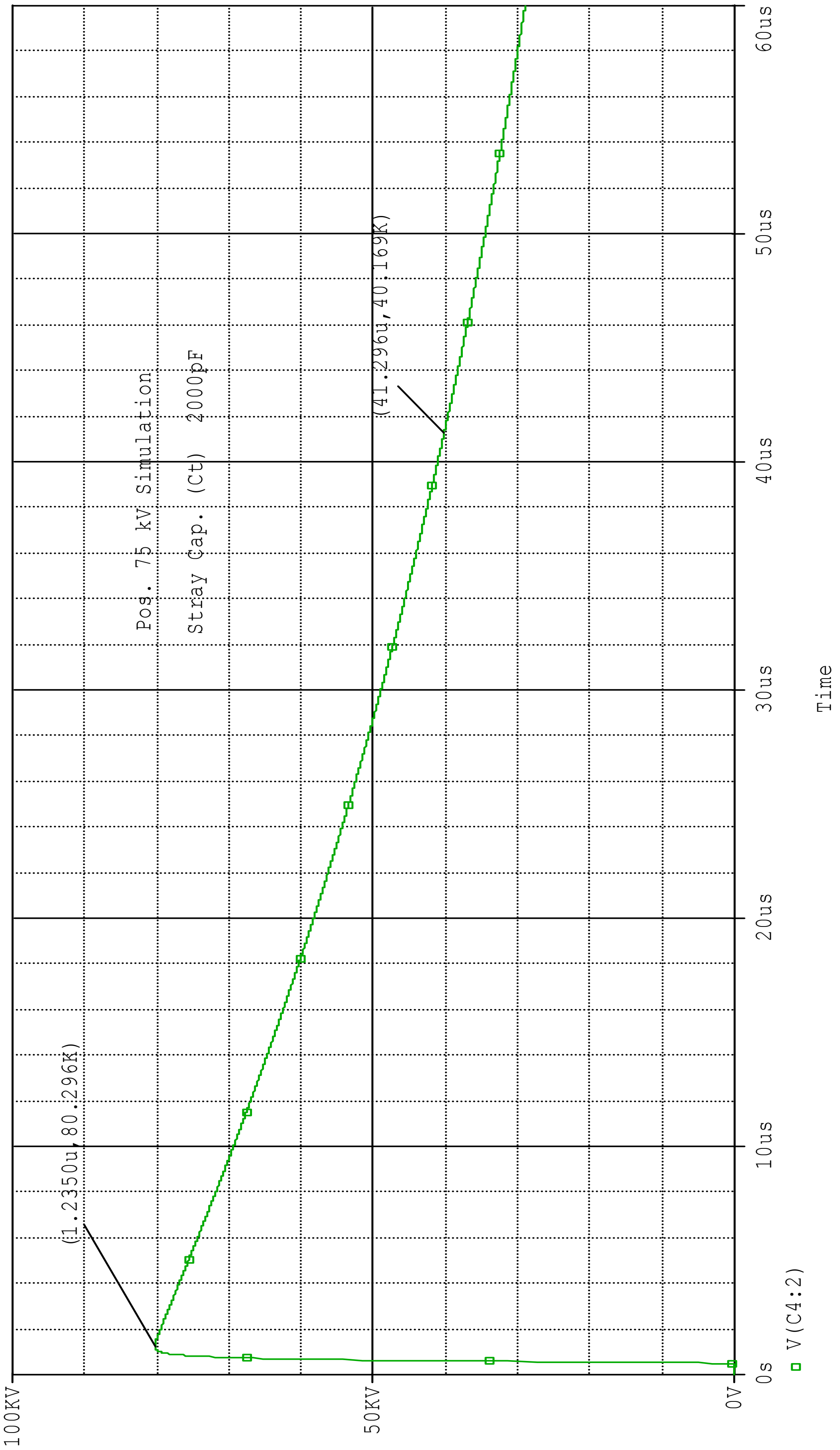

Figure 16 75kV Positive SPICE Simulation.

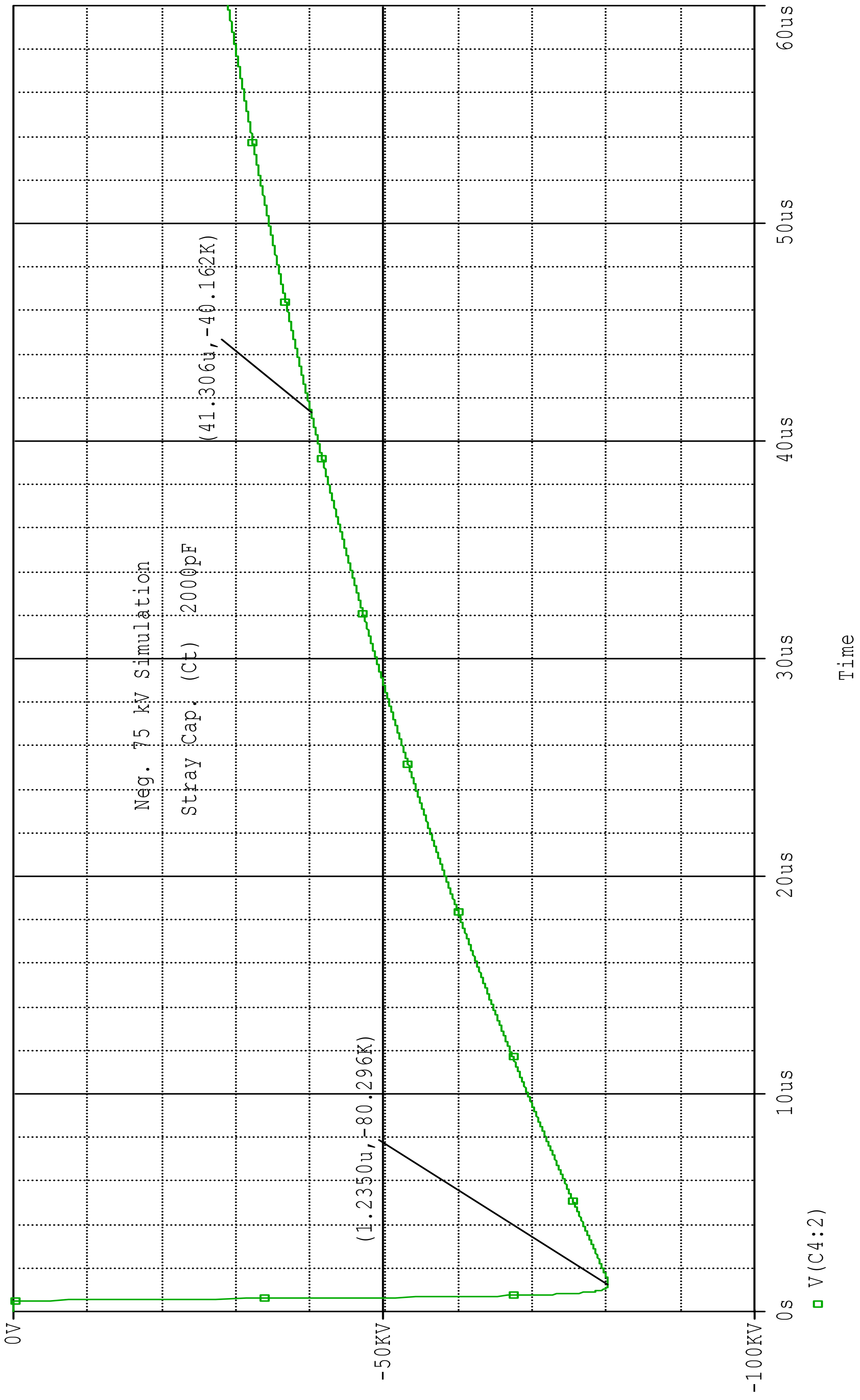

Figure 17 75kV Negative SPICE Simulation.

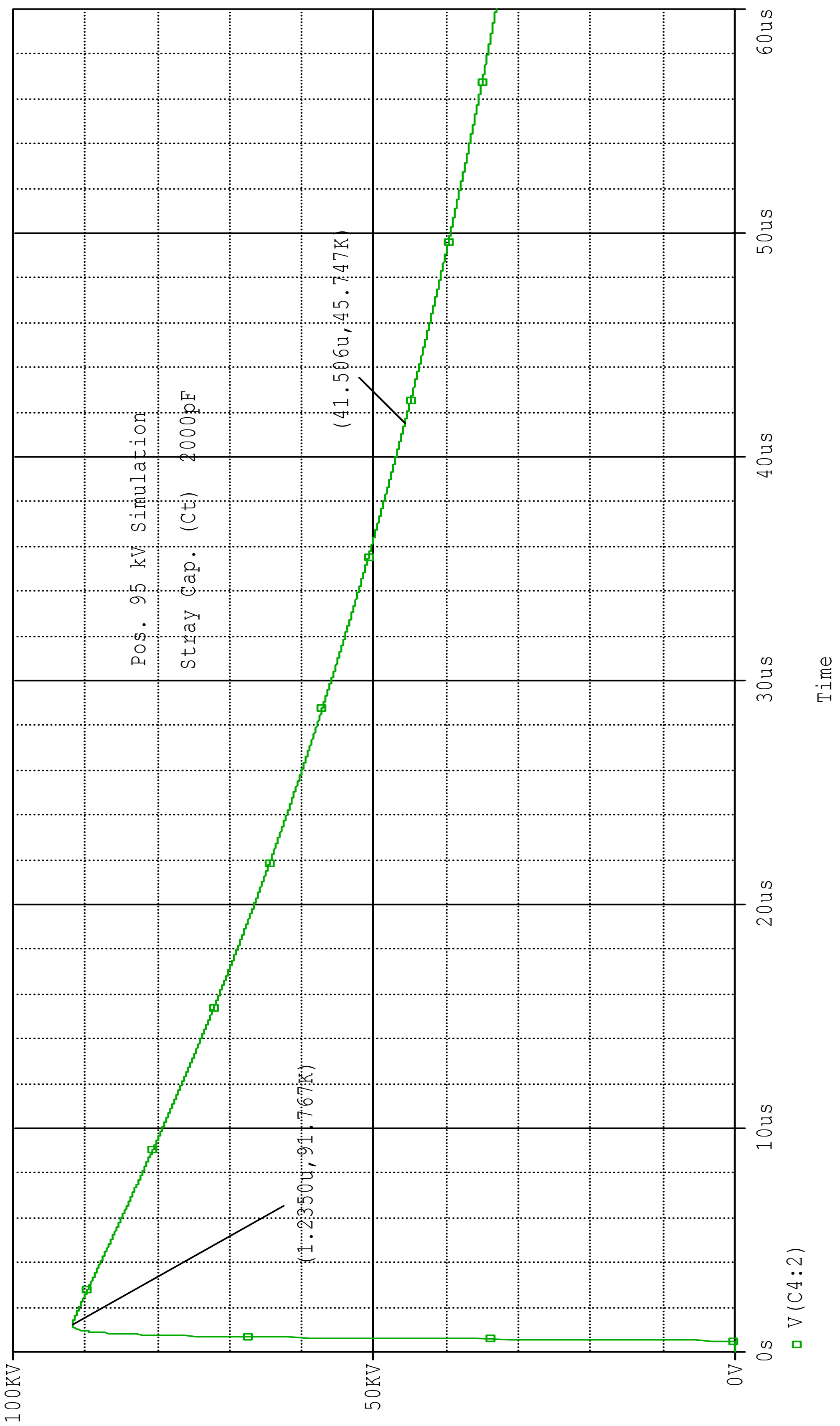

Figure 18 95kV Positive SPICE Simulation.

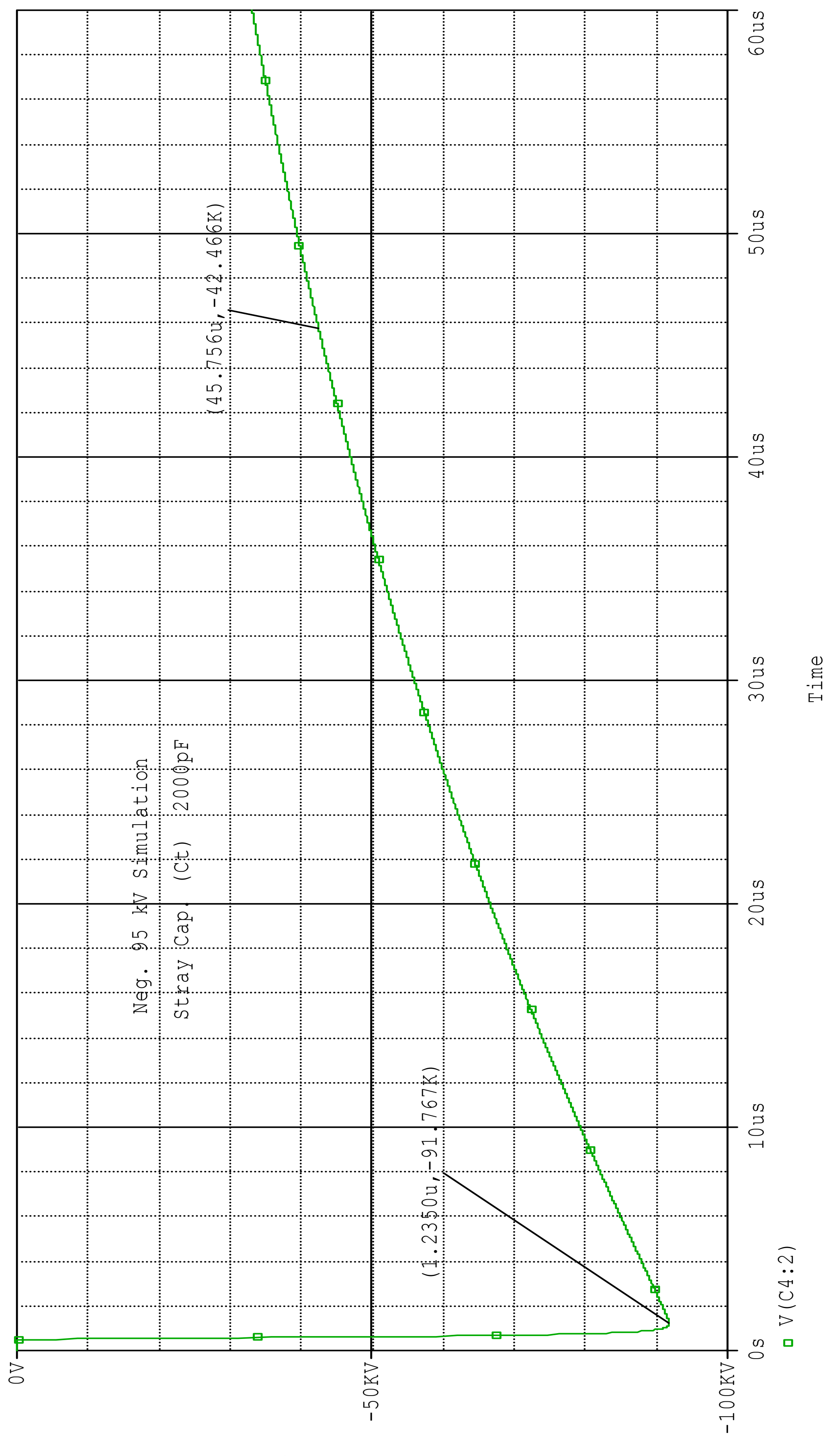

Figure 19 95kV Negative SPICE Simulation.

Table 5 is a comparison of the experimental and simulation results. The peak voltage value resulting for both the simulation and experimental testing is easily compared. During the experimental testing the rise time was checked to IEEE Standard 4 and found to be within calibration. It is shown from Table 5 that the results are fairly close when the actual impulse generator charging voltage is used as the initial condition for the stage capacitors in SPICE. The error is greatest at the negative 62.5 kV test level when compared to both the 75 and 95 kV levels.

Table 5 Comparison of Test Data, Peak Voltage

kV Test Level	(+ or -)	Charge kV	Measured Avg. kV	Corrected Avg. kV	SPICE	
					Charge	kV
62.5	+	23	62.1	63.4	23 kV	65.9
	-		-61.3	-62.5		-65.9
75	+	28	79.1	80.8	28 kV	80.3
	-		-79.0	-80.7		-80.3
95	+	32	91.6	93.6	32 kV	91.8
	-		-92.1	-94.0		-91.8

The effect of the stray capacitance to ground, Ct, is in the rise time to peak of the wave. In the SPICE circuit the value arrived at for stray capacitance was 2000pf. The estimated value for stray capacitance is 20.8pF and when used in the simulation the rise time was out of tolerance. The pre-load capacitor actual value is 0.002µf and the simulation required the stray capacitance to be equal to the pre-load capacitance to attain the 1.2µs rise time to peak.

The test peak values for impulse testing are too high to directly measure. The test setup using the impulse generator and a voltage divider which allows for measurement of a representative lower voltage value on an oscilloscope. This lower value is corrected using multiplication factors that are calibrated to atmospheric parameters at the time of testing. This method has been utilized and refined over many years of practice. Standards have been developed for high voltage testing which define allowable tolerances for the measured wave shapes.

Figure 20 depicts a comparison of the SPICE wave and the base wave from the laboratory testing. These waves were taken from separate programs and then plotted using Excel. The simulation generated wave points were taken and then entered into the same Excel file. This allowed the two curves to be plotted on the same axis for comparison. As observed from Figure 20 the waves are very close.

Comparing the timing of the voltage waves reveals that the SPICE simulation is also within IEEE tolerance and nearly matches the base on the front of wave (T1). See Table 6 for the values of the base and simulation circuit. The simulation front of wave time to peak voltage is 0.01µs slower than the impulse generator or within 0.8 percent of the actual base time. The tail time (T2) of the wave to one-half of the peak voltage is shorter by 3.1µs, 6.9 percent for the simulation.

Table 6 Comparison of Wave Times

	Front Time (T1)		Tail Time (T2)	
Polarity	Base(Avg) (micro-s)	SPICE (micro-s)	Base(Avg) (micro-s)	SPICE (micro-s)
Positive	1.22	1.23	44.5	41.4
Negative	1.19	1.23	58.2	41.4

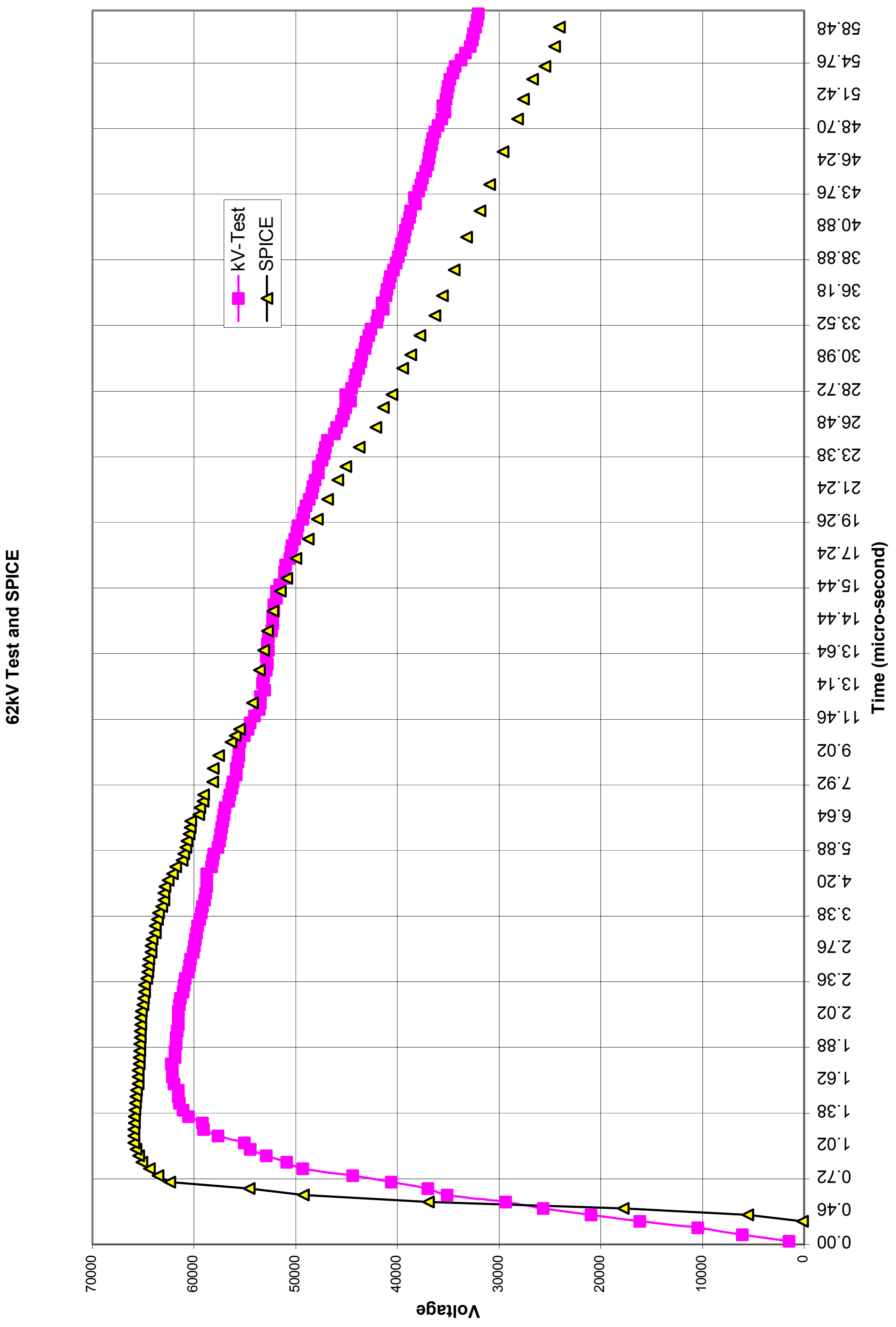

Figure 20 Comparison 62kV Test and SPICE Wave Shapes

7.0 CONCLUSIONS

The simulation circuit, with the stray capacitance added, closely approximated the actual base impulse generator. The front of wave rise time (T1) to peak voltage was within 0.8 percent of that recorded in calibration of the impulse generator. This value of time is directly influenced by the capacitance of the divider and the pre-load capacitor itself. The resistance value of the stage front resistor also has an impact on the time to peak and, in actual impulse generators, this value is adjusted to correct the time to be in tolerance.

The wave shape tail-time to one-half the peak voltage had a larger difference between the simulation and the actual impulse generator. This value is largely controlled by the value of the tail resistor in each generator stage. For purposes of this thesis the value of the actual tail resistor was used in the simulation and resulted in the wave tail time (T2) within tolerance.

The peak voltage also was well within tolerance and closely approximated the base impulse generator. The initial charge of each stage capacitor is the most common method of adjusting the actual peak test output voltage. Typically the actual value of charging voltage used for each stage capacitor is the calibrated value.

Overall the simulation circuit resulted in close to actual impulse generator 1.2 x 50μs wave shape for all three test voltages. The simulation circuit could be used to preset the surge set for desired test wave peak voltage. This would save expense and time by not actually performing test impulse attempts.

APPENDIX

Impulse Test Form

Page__of__

Enclosure Type : Style No.
Equipment Id :
Breaker Type : Mech. Type :
Pole Type : Discon. Type :
Breaker Serial No. Project No:
VI Type WL- Engineer:

62 kV 1.2 X 50 µs B.I.L. Test Data
____ 2 µs Chopped Wave at 142 kV Test Data
____ 3 µs Chopped Wave at 126 kV Test Data

☐ Conformance Tests per ANSI C37.54 -1987, Sec. 3.4

	CONDITIONS	
	BEFORE	AFTER
Time	8:15	
Pm = Pres. Measured	765.81 mm hg	mm hg
T° K= (T °C)+273.15	28.0 °C 301.15 °K	°C °K
Relative Humidity	31%	

Scope Settings

Fisher Scientific Digital Barometer Calibrated: 4/30/01 Due: 4/30/02	Hipotronics Impulse Generator Calibrated 10/27/00 Due 10/27/01	Vertical Scale =	100 Volts/Div.
		Horizontal Scale =	10 µs /Div.
Correction Factor	Tektronix TDS 544A Digitizing Scope	Multiplier + (pg. 4 2000 Calibration)	140.14 kV/V
0.3855 x Pressure Measured / Temp. °K: .980	Calibrated 1/25/01 Due 1/25/02	Multiplier - (pg. 4 2000 Calibration)	141.63 kV/V

ANSI/IEEE STD. 4-1978
Approved 4-26-1982

POL	Picture	Charging	MEAS	CORR	Bkr		TERMINALS		TRIAL : Pass =√ Fail =X															Actual Scope Reading
+/-	#	(kV)	PEAK kV	PEAK kV	C/T	O/C	ENERGIZED	GROUNDED	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
+	000	23.0	62.2	63.5	N/A	N/A	N/A	N/A	✓															444,
+	001	23.0	62.2	63.5					✓															444
+	002	23.0	61.9	63.2					✓															442
-	003	23.0	61.2	62.4					✓															-432
-	004	23.0	61.2	62.4					✓															-432
-	005	23.0	61.5	62.7					✓															-434

TEST INSPECTION & COMMENTS:

Witness Name :
Organization or
Company : Cutler-Hammer RIDC Park West 170 Industry Dr. Pittsburgh, Pa. 15275
Lab Technician : James B. Jamison Date : 9/14/01
Lab Technician : Date :

00bilfrm.xlt

Impulse Test Form

Page__of__

Enclosure Type : ________ Style No. ________
Equipment Id : ________
Breaker Type : ________ Mech. Type : ________
Pole Type : ________ Discon. Type : ________
Breaker Serial No. ________ Project No: ________
VI Type WL- ________ Engineer: ________

75 kV 1.2 X 50 µs B.I.L. Test Data
____ 2 µs Chopped Wave at 142 kV Test Data
____ 3 µs Chopped Wave at 126 kV Test Data

☐ Conformance Tests per ANSI C37.54 -1987, Sec. 3.4

	CONDITIONS BEFORE	CONDITIONS AFTER
Time	8:45	
Pm = Pres. Measured	765.81 mm hg	mm hg
T° K= (T °C)+273.15	28.5 °C 301.65 °K	°C °K
Relative Humidity	31%	

Scope Settings

Fisher Scientific Digital Barometer Calibrated: 4/30/01 Due: 4/30/02	Hipotronics Impulse Generator Calibrated 10/27/00 Due 10/27/01	Vertical Scale = 200 Volts/Div. Horizontal Scale = 10 µs /Div.
Correction Factor 0.3855 x Pressure Measured / Temp. °K .979	Tektronix TDS 544A Digitizing Scope Calibrated 1/25/01 Due 1/25/02	Multiplier + (pg. 4 2000 Calibration) 145.37 kV/V Multiplier - (pg. 4 2000 Calibration) 150.40 kV/V

ANSI/IEEE STD. 4-1978
Approved 4-26-1982

POL +/-	Picture #	Charging (kV)	MEAS PEAK kV	CORR PEAK kV	Bkr C/T	Bkr O/C	TERMINALS ENERGIZED	TERMINALS GROUNDED	TRIAL : Pass =√ Fail =X 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Actual Scope Reading
-	006	28.0	78.8	80.5	N/A	N/A	N/A	N/A	✓															-524
-	007	28.0	78.8	80.5					✓															-524
-	008	28.0	79.4	81.1					✓															-528
+	009	28.0	79.1	80.8					✓															544
+	010	28.0	79.1	80.8					✓															544
+	011	28.0	79.1	80.8					✓															544

TEST INSPECTION & COMMENTS: ________

Witness Name : ________
Organization or
Company : Cutler-Hammer RIDC Park West 170 Industry Dr. Pittsburgh, Pa. 15275
Lab Technician : James B. Jamison Date : 9/14/01
Lab Technician : ________ Date : ________

Impulse Test Form

Page__of__

Enclosure Type : ________ Style No. ________
Equipment Id : ________
Breaker Type : ________ Mech. Type : ________
Pole Type : ________ Discon. Type : ________
Breaker Serial No. ________ Project No: ________
VI Type WL- ________ Engineer: ________

95 kV 1.2 X 50 µs B.I.L. Test Data
____ 2 µs Chopped Wave at 142 kV Test Data
____ 3 µs Chopped Wave at 126 kV Test Data

☐ Conformance Tests per ANSI C37.54 -1987, Sec. 3.4

	CONDITIONS	
	BEFORE	AFTER
Time	9:05	
Pm = Pres. Measured	765.81 mm hg	mm hg
T° K= (T °C)+273.15	28.5 °C 301.65 °K	°C °K
Relative Humidity	31%	

Scope Settings

Fisher Scientific Digital Barometer Calibrated: 4/30/01 Due: 4/30/02	Hipotronics Impulse Generator Calibrated 10/27/00 Due 10/27/01	Vertical Scale =	200 Volts/Div.
		Horizontal Scale =	10 'µs /Div.
Correction Factor	Tektronix TDS 544A Digitizing Scope Calibrated 1/25/01 Due 1/25/02	Multiplier + (pg. 4 2000 Calibration)	148.07 kV/V
0.3855 x Pressure Measured / Temp. °K .979		Multiplier - (pg. 4 2000 Calibration)	152.42 kV/V

ANSI/IEEE STD. 4-1978
Approved 4-26-1982

POL	Picture	Charging	MEAS	CORR	Bkr		TERMINALS		TRIAL : Pass =√ Fail =X															Actual Scope Reading
+/-	#	(kV)	PEAK kV	PEAK kV	C/T	O/C	ENERGIZED	GROUNDED	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
+	012	32.0	91.2	93.2	N/A	N/A	N/A	N/A	✓															616
+	013	32.0	91.8	93.8					✓															620
+	014	32.0	91.8	93.8					✓															620
-	015	32.0	91.4	93.4					✓															-600
-	016	32.0	92.7	94.6					✓															-608
-	017	32.0	92.1	94.0					✓															-604

TEST INSPECTION & COMMENTS: ________

Witness Name : ________
Organization or
Company : Cutler-Hammer RIDC Park West 170 Industry Dr. Pittsburgh, Pa. 15275
Lab Technician : James B. Jamison Date : 9/14/01
Lab Technician : ________ Date : ________

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