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Construction of a High Speed Buffer Amplifier to Measure Lightning Generated Vertical Electric Fields

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ABSTRACT

A high-speed Buffer Amplifier circuit was constructed with a buffer Amplifier IC OPA633 that can be coupled to a parallel plate antenna via 60cm coaxial cable to measure the lightning generated vertical electric fields. The use of a high speed buffer amplifier isolates the high impedance of the antenna and offers enough power to drive the signal from the antenna to the recording unit through a coaxial cable. The electric field measured by this circuit represent the actual strength of the electric field normal to the ground. According to the frequency response of the circuit, it is seen that the circuit is suitable in recording lightning generated electric fields up to MHz region. It has been successfully used in field tests in recording lightning generated electric fields during the months of December & January.

1. INTRODUCTION

During fine weather, the electric field near the surface of the earth varies slowly during the course of the day. It is relatively steady and show small gradients during fine weather. The electric field and its variations during thundery weather differ in two main aspects from those encountered during fine weather. First, the electric field may rise to many thousands of volts/meter, and secondly, electric field undergoes rapid changes during the development of a lightning flash. A number of methods have been devised and used in the past to measure the lightning generated electric fields. The Capillary Electrometer method, Point Discharge method and Amplifier-Oscilloscope method are some of those. These methods use different types of field sensors to measure lightning generated electric fields.

They are:
- Vertical Conductor
- Sphere Antenna
- Flat Plate Antenna (or Parallel Plate Antenna)

Vertical antennas are generally not used to measure the fields of close lightning flashes because of corona discharges that occur from the tip of the antenna which can be superimposed on the measured signal. The Flat plate antenna (or Parallel plate antenna) is designed to measure the Vertical Electric Field at ground level. In this work we used the Amplifier-Oscilloscope method.

2. THEORETICAL BACKGROUND

In the case of lightning generated electric field measurements carried out by using a flat plate antenna, the quasi-static theory is applicable. Hence one can use the Gauss's Law, which links the charge in a region or on a surface to the electric field.

From Coulomb's law,

Electric Field
$$E = \frac{F}{Q} = \frac{Q}{4\Pi\varepsilon_0\varepsilon_r r^2} \qquad (1)$$

Electric Flux Density
$$D = \frac{Q}{4\Pi r^2} = E\varepsilon_0\varepsilon_r \qquad (2)$$

According to the Gauss's law,

$$\int D.ds = Q \quad \Rightarrow \quad D.S = Q$$

where S is area of the plate.

From (2),

Normal Electric Field
$$E_n = \frac{Q}{\varepsilon_0\varepsilon_r S} \qquad (3)$$

The voltage between the flat plate and the ground,

$$V_g = -\int E_n.\ dx = \frac{Q.d}{\varepsilon_0\varepsilon_r S}$$

$$\Rightarrow \quad V_g = E_n.\ d$$

This indicates that the voltage V_g is proportional to the change in the Electric Field (produced by the lightning flashes) normal to the flat plate antenna.

3. ELECTRIC FIELD MEASURING SYSTEM

Figure 1 shows the block diagram of a typical electric field measuring system.

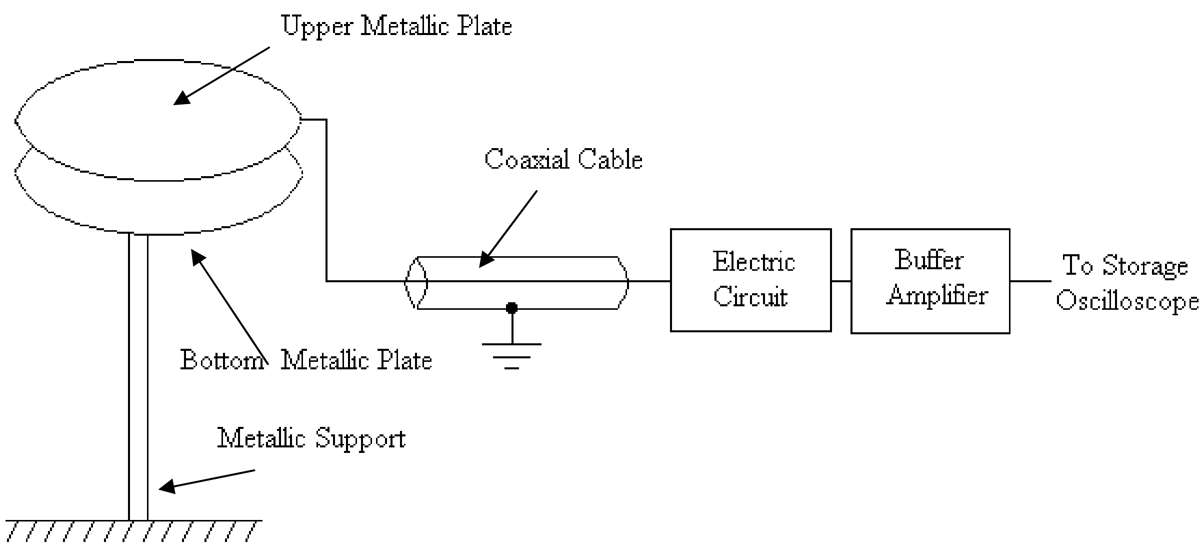
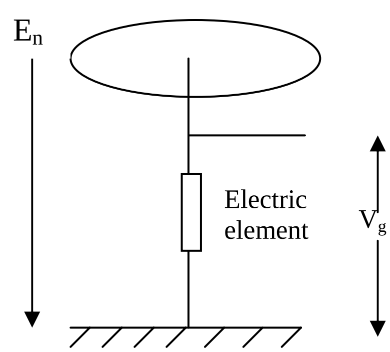


Figure 1: Block diagram for the electric field measuring system

3. 1 The electric element

The amplifier – Oscilloscope method can be used to investigate rapid changes in electric field caused by lightning discharges.

Depending on the electric element, which will be used in measuring the current, we obtain either the normal electric field or the derivative of the electric field.



3. 1. 1 Case 1 - Resistor as an electric element

$$I = dQ/dt \;\&\; V_g = Ri$$

From (3)

$$V_g = \varepsilon_0 \varepsilon_r RS\, (dE_n/dt)$$

Voltage V_g depends on the derivative of the electric field.

3. 1. 2 Case 2 - Capacitor as an electric element

$$Q = V_g \,.\, C \quad \& \quad Q = \int i\,dt$$

From (3)

$$V_g = (\varepsilon_0 \varepsilon_r S / C).\, E_n$$

Voltage V_g depends on the normal electric field E_n.

Due to the difficulties in the interpretation of the records, for the present work, a capacitor was used as an electric element. Hence the electric field measured by this circuit is the actual electric field normal to the ground.

3. 2 Equivalent circuit of the system

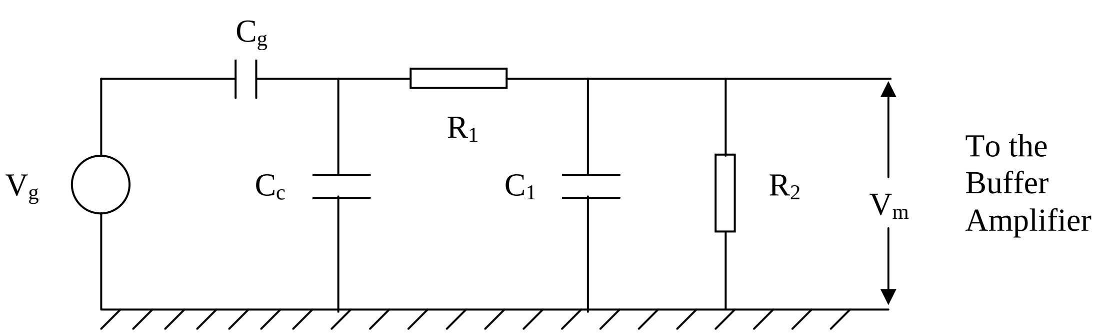


Figure 2: Equivalent circuit of the system

In Figure 2 the equivalent circuit of the system is shown. In this circuit, C_g is the capacitance of the parallel plate antenna. The antenna used in this work had a capacitance of 59pF. C_c is the capacitance of the 60cm length coaxial cable (see figure 1) which is used to link the antenna and the electric circuit. The capacitance of the cable is 60pF.

C_1 is the capacitor used as an electric element to measure the electric field by measuring the changes in the voltage V_g of the parallel plate. A 15pf capacitor was used as the electric element. Capacitor C_1 was shunted by high value resistor R_2 that controls the decay time constant $C_1.R_2$. Since the input impedance of the buffer amplifier is very high (in the order of $10^{13}\Omega$), a 100MΩ resistor was used at R_2 to increase the time constant.

R_1 is a 50Ω resistor used at the entrance of the electric circuit to terminate the characteristic impedance of the coaxial cable that link the antenna and the electric circuit.

According to the Thevenins equivalent analysis,

$$\frac{V_m}{V_g} = \left(\frac{sC_g R_2}{1 + s(R_1 + R_2)\,.\,(C_g + C_c) + sF_1} \right)$$

where $F_1 = R_2[\,C_1 + sR_1\,.\,C_1\,(C_g + C_c)]$ and $s = j2\Pi f$. The frequency response of the circuit can be calculated by the above equation.

The decay time constant of the circuit,

$$\tau = (C_1 + C_g + C_c).\,R_2$$

$$\tau = 13.4 \text{ ms}$$

This is large enough to record lightning generated electric field signals with a high accuracy.

4. THE BUFFER AMPLIFIER

Since we are using the amplifier – oscilloscope method to measure the lightning generated electric fields, a amplifier circuit has to designed in such a way that the parameters of interest (ie. amplitude and risetime) of the lightning generated electric fields can be measured with a reasonable precision. In order to achieve this objective we must use a high-speed buffer amplifier circuit. The use of a high speed buffer amplifier isolates the high impedance of the antenna and offers enough power to drive the signal from the antenna to the recording unit through the coaxial cable.

The OPA633 IC from the Burr-Brown is a very good match for our requirement. The OPA633 is a monolithic unity gain high-speed buffer amplifier featuring very wide bandwidth (260 MHz) and high slew rate (2500 V/μs). High output current capability (100mA) allows the OPA633 to drive 50Ω lines (see figure 3).

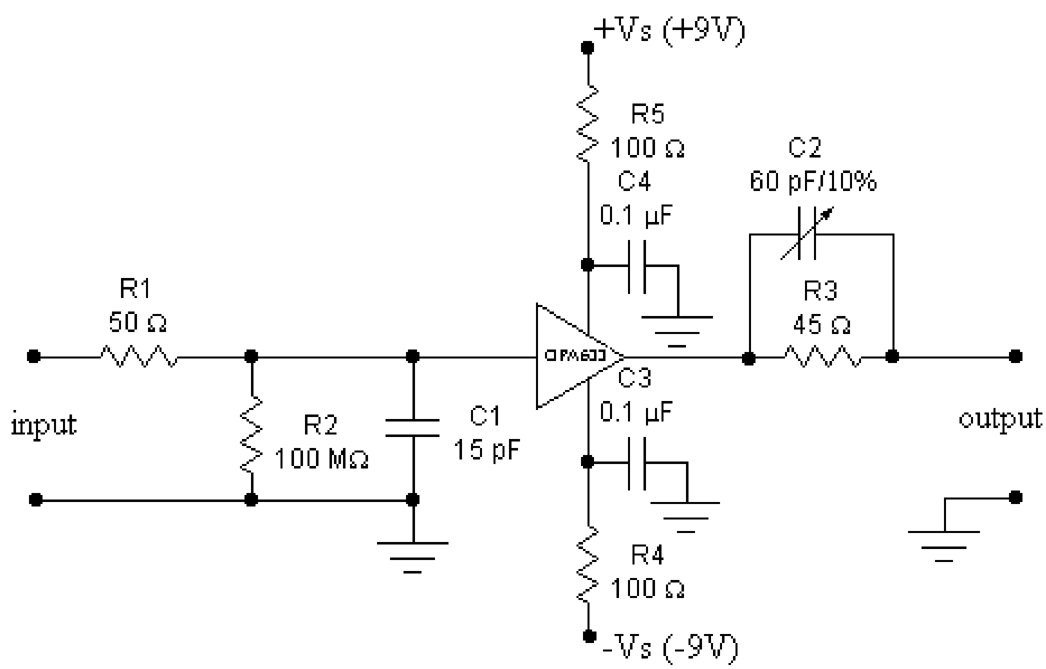


Figure 3: Circuit diagram of the buffer amplifier circuit

4. 1 Design of the circuit layout

To achieve optimum performance in measuring high frequencies, special attention was given to the design of the circuit layout. Power supply connections are bypassed with two high frequency ceramic capacitors (i.e. Two 0.1μF capacitors -C3 &C4 in figure 2). They were placed as close as possible to the buffer amplifier IC's power supply pins for high frequency decoupling. To protect the circuit from damages due to excessive currents, a resistor in series with the power supply pins was added (i.e. Two 100Ω resistors–R4 &R5 in figure 2). A large ground plane was used to minimize high frequency ground drops and stray coupling.

Since we are using this system in a high frequency region, it is important to match the load to the characteristic impedance of the line. Therefore we used 45Ω resistor (R_3 in figure 3) as the back termination resistor series with the Buffer Amplifier IC's output line. Since the output impedance of the OPA633 IC is 5Ω, the total termination resistor is 50Ω. Hence we can easily use 50Ω coaxial cable as the signal transmission line to send the signals to the recording unit. To optimize the circuits pulse response, a capacitor C_2 in figure 3 (60pF/10% variable capacitor) was connected across the series back termination.

4.2 Frequency response of the buffer amplifier circuit

We observed that the measured voltage V_m is less than the V_g, because the RC circuit attached to the parallel plate antenna loads the antenna. Table 1 shows the observations of the frequency domain for the circuit.

Table 1: Observations of the Frequency Domain for the Circuit

f(Hz)	V_m/V_g	f(Hz)	V_m/V_g	f(Hz)	V_m/V_g	f(Hz)	V_m/V_g	f(Hz)	V_m/V_g
1	0.034	10	0.201	100	0.394	1×10^3	0.435	1×10^4	0.440
2	0.063	20	0.276	200	0.416	2×10^3	0.438	1×10^5	0.440
3	0.089	30	0.315	300	0.424	3×10^3	0.439	1×10^6	0.440
4	0.111	40	0.339	400	0.428	4×10^3	0.439	1×10^7	0.440
5	0.130	50	0.356	500	0.430	5×10^3	0.439	1×10^8	0.440
6	0.148	60	0.368	600	0.432	6×10^3	0.439	1×10^9	0.440
7	0.163	70	0.376	700	0.433	7×10^3	0.440	1×10^{10}	0.440
8	0.177	80	0.383	800	0.434	8×10^3	0.440		
9	0.190	90	0.389	900	0.435	9×10^3	0.440		

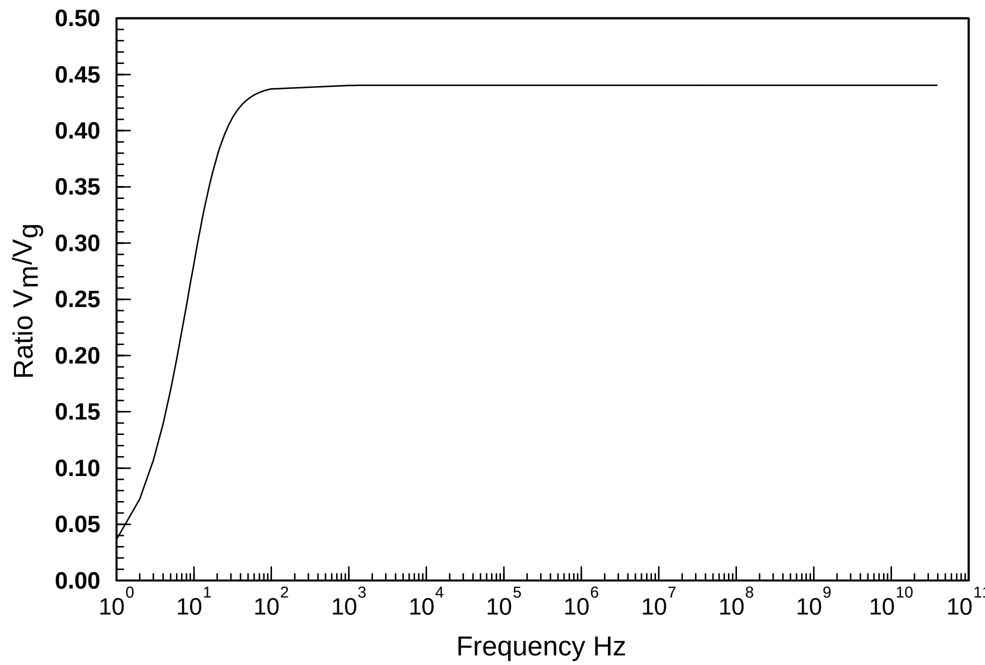


Figure 4: Frequency response of the buffer amplifier

5. DISCUSSION & CONCLUSIONS

The sensing antenna has to be located far away from the recording unit in order to avoid any distortion of the lightning electric fields. The amplifier is designed to safely drive capacitive loads up to 0.01μF. Hence up to a maximum of 100m length coaxial cable between the recording unit and the amplifier can be used to avoid distortions.

The circuit discussed here has been successfully used in field tests in recording lightning generated electric fields during the months of December & January.

This circuit discussed here is suitable for recording field changes lasting for times shorter than a few milliseconds. Slower field changes could be recorded by increasing the time constant of the electric circuit, but this requires stringent conditions of the insulation and the amplifier response. Since a proper calibration is needed before using in an actual measurement, the instrument has been sent to Uppsala University of Sweden for calibration.

ACKNOWLEDGEMENT

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