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Journal of Electrostatics 63 (2005) 285–296

Journal of ELECTROSTATICS

www.elsevier.com/locate/elstat

Spark protection circuit for measuring current in high-voltage circuits

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Received 29 June 2004; received in revised form 13 October 2004; accepted 15 October 2004

Abstract

A circuit has been designed to protect electrometers and other sensitive instrumentation from damage by electrical sparks. Measuring current is necessary in a variety of high-voltage applications, including the evaluation of ionizers designed to eliminate static charge. The currents are often small, perhaps only several microamperes (μA) or less. Instruments designed to accurately measure such small currents are expensive and sensitive. Consequently, the instruments are susceptible to damage from unexpected electrical sparks that are common in high-voltage experiments.

The protection circuit has two layers of protection. The first layer is a Zener Transient Voltage Suppressor that limits the input voltage by shunting the spark energy to ground potential. The second layer of protection is a passive, low-pass filter that blocks the high-frequency energy of the spark while passing the low-frequency current to be measured.

The filter design is based on a resistively terminated, LC Cauer network. Three inductors are required to obtain high-frequency attenuation exceeding 10^{+6}, resulting in a sixth-order low-pass filter. Small resistances to ground through connectors and cables, that are normally negligible, limit the high-frequency attenuation to about 10^{+5}, which provides sufficient protection.

Keywords: Spark protection; ESD; High voltage; Instrumentation; Circuit; Damage; Discharge; Filter

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doi:10.1016/j.elstat.2004.12.002

1. Introduction

It is well known that sparks can damage electrical components. Effective methods to protect components from electrostatic discharge (ESD) are practiced [1], which typically involve connecting a diode from an input to ground or a DC power source. One challenge is to design the protection diode so that the instantaneous high current of the spark can be shunted to AC ground without damaging the diode.

In applications where devices such as corona ionizers are energized by high voltage, sparks can be significantly more energetic than common ESD events. Reported here is a circuit designed to protect sensitive instruments from energetic sparks.

The spark protection circuit is a passive, low-pass filter. When there are no sparks, DC and low-frequency AC signals are passed without attenuation, preserving the information content in the signal. When sparks occur, the high-frequency energy is shunted to ground, protecting sensitive instruments connected to the output of the filter. A passive realization using robust components prevents spark damage to the protection circuit.

The circuit design overcomes a key challenge. The impedance of real inductors deviates significantly from ideal. High-frequency energy must be attenuated, even though the inductors have limited frequency response. This is accomplished by using a capacitive divider strategy that achieves a high-frequency attenuation of 10^{+5}.

2. Circuit design

2.1. Second order filter analysis

Fig. 1 is a diagram of a common, experimental method for measuring the output current of a corona ionizer. A high-voltage power supply with an output voltage, V_{HV}, energizes a corona charger. In the event of a spark, a series resistor $R_{\mathrm{Current\text{-}Limit}}$ limits current. Current flows in a corona field from the charger to a plate electrode located below the charger. The electric current I_{Corona} collected by the plate electrode is monitored by an electrometer. If the high voltage is too big,

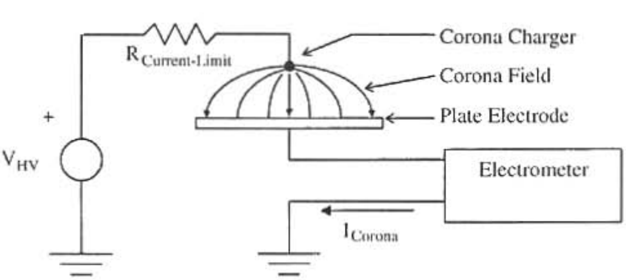

Fig. 1. Shown is a common method for measuring the output current of a corona ionizer. The electrometer is at risk for damage by a spark from the corona charger to the ground-plate electrode.

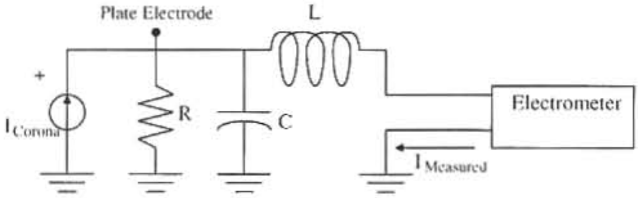

Fig. 2. For simplicity, the power supply and corona ionizer shown in Fig. 1 are modeled as a current source. The electrometer is protected from spark damage by a second-order low-pass filter. The electrometer is still at risk for damage by a current pulse from the current source because stray capacitance across the coils of the inductor passes high-frequency current.

a spark from the corona charger to the plate electrode will occur. This spark can damage the electrometer.

One proposed method of protecting the electrometer from damage is shown in Fig. 2. The current from the corona wire collected by the plate electrode is represented by a current source that energizes the circuit. For ideal components, the transfer function [2] for this circuit is given in (1) where s is the complex

$$\frac{I_{\text{Measured}}}{I_{\text{Corona}}} = \frac{1/LC}{s^2 + s(1/RC) + 1/LC}. \tag{1}$$

frequency defined in the Laplace transform [3]. In normal operation, when there is no spark, the input impedance of the electrometer is negligibly small. As s approaches zero, the transfer function approaches unity, therefore this is a low-pass filter with unity gain at low frequency. The cut-off frequency is

$$f_{\text{cut-off}} = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}}. \tag{2}$$

The inductor and capacitor are selected to provide the desired cutoff frequency. The resistor R can be selected to provide maximally flat frequency response at low frequency,

$$R_{\text{maximally-flat}} = \sqrt{\frac{L}{2C}}. \tag{3}$$

2.2. Frequency response of real inductors

The electrometer in the circuit shown in Fig. 2 is still at risk of spark damage because the frequency response of real inductors deviates significantly from the response of an ideal inductor. At high frequencies, stray capacitance across the windings of the inductor is significant as illustrated in Fig. 3. The frequency response of a real inductor can be determined from the circuit model shown in Fig. 4 which includes the stray capacitance and winding resistance.

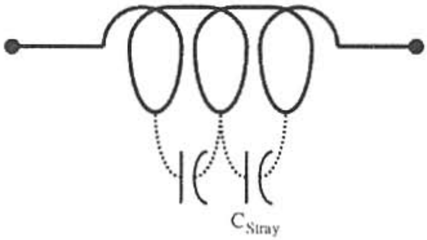

Fig. 3. Stray capacitance across the windings of an inductor dominates at high frequencies. At high frequency, above the self-resonant frequency or SRF, an inductor has a capacitive frequency response.

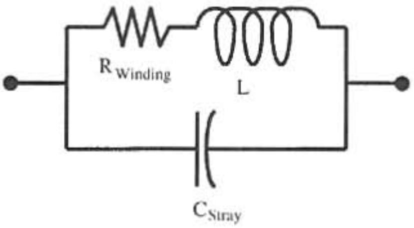

Fig. 4. Shown is the circuit model for a real inductor that includes stray capacitance between the windings and the winding resistance. At high frequency, the response is capacitive, which allows spark energy to pass.

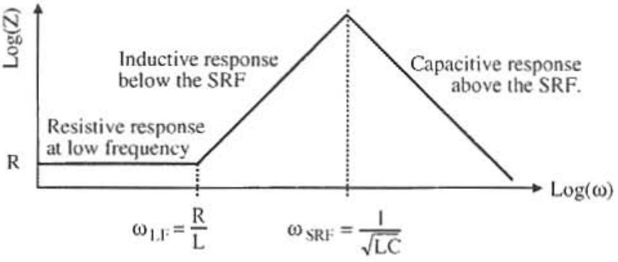

Fig. 5. The impedance of an inductor is dominated by stray capacitance across the windings at high frequency, above the self-resonant frequency or SRF.

The impedance of this circuit in given in (4), and the frequency response is illustrated in Fig. 5.

$$Z(s) = \frac{1}{C}\frac{s + (R/L)}{s^2 + s(R/L) + 1/LC}. \tag{4}$$

For a 10 mH inductor with a winding resistance R of 0.2 Ω and a self-resonant frequency (SRF) of 200 kHz, the characteristic frequency ω_{LF} is 20 rad/s (3 Hz), and the stray capacitance is about 60 pF.

At high frequency, above the SRF of the inductor, the protection circuit shown in Fig. 2 behaves as a capacitive divider as illustrated in Fig. 6.

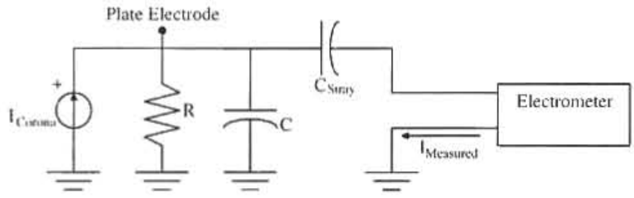

Fig. 6. The attenuation of the high frequency spark energy is determined by the stray capacitance of the inductor. An inductor with a very high SRF is required to adequately protect the electrometer.

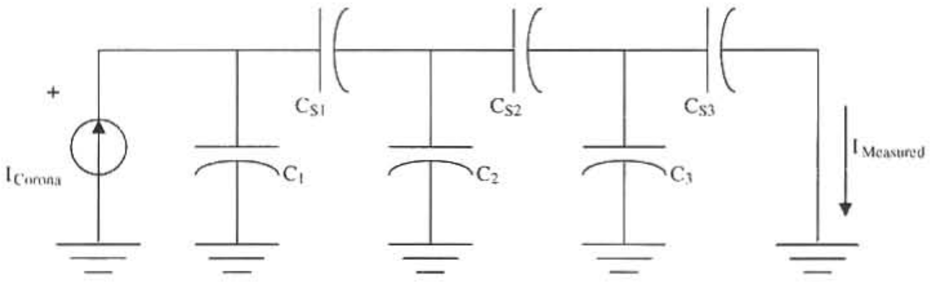

Fig. 7. This three-stage capacitive divider provides greater attenuation of the high-frequency spark energy than the one-stage divider, illustrated in Fig. 6.

The transfer function for this circuit is given in (5) where the input impedance of the electrometer is negligible relative to the other circuit impedances.

$$\frac{I_{\text{Measured}}}{I_{\text{Corona}}} = \left(\frac{C_{\text{Stray}}}{C + C_{\text{Stray}}}\right)\frac{s}{s + 1/R(C + C_{\text{Stray}})} \tag{5}$$

Assuming that the stray capacitance C_{Stray} is small relative to the capacitor C, the attenuation of the high-frequency spark current is approximately (C_{Stray}/C). For circuits designed to have cut-off frequencies in the range of 100 Hz to 10 kHz, capacitive components will be on the order of 10 nF and the attenuation will be in the range of $\frac{1}{100} - \frac{1}{1000}$. For this design, with a stray capacitance of 60 pF, the attenuation will be about $\frac{1}{160}$.

2.3. Capacitive divider strategy

The high-frequency attenuation can be greatly increased by adding stages to the capacitive divider. Fig. 7 illustrates a capacitive divider with three stages. The transfer function of this circuit, with the approximation that the stray capacitances are small, is given in

$$\frac{I_{\text{Measured}}}{I_{\text{Corona}}} = \left(\frac{C_{S1}}{C_1}\right)\left(\frac{C_{S2}}{C_2}\right)\left(\frac{C_{S3}}{C_3}\right). \tag{6}$$

for this circuit with capacitive components of about 10 nF, the attenuation is estimated to be $(1/160)^3$ or about $1/(4 \times 10^{+6})$.

2.4. Sixth-order filter design

Fig. 8 shows the spark protection circuit designed using standard analog filter design techniques for passive realization with lossy inductors [4]. The circuit design was evaluated using SIMPLORER® Simulation System Version 6.0 SV [5], and the results are shown in Fig. 9. Two cases are shown. The solid line is the gain $I_{Measured}/I_{Corona}$ as a function of frequency when ideal inductors are used. As

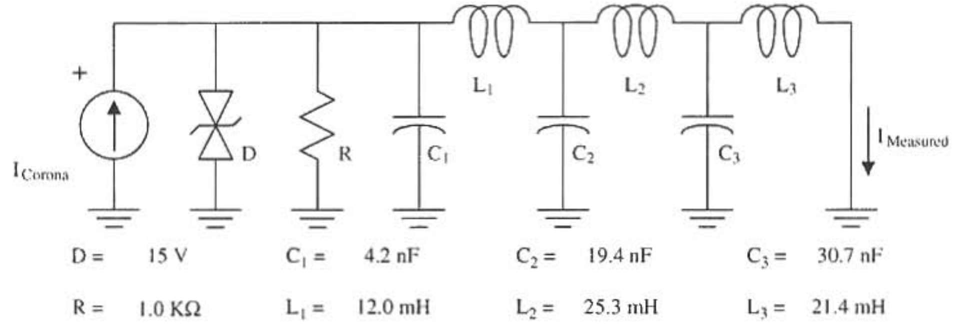

Fig. 8. This sixth-order, maximally flat, low-pass filter has a cut-off frequency of 10 kHz. The high-frequency attenuation exceeds 10^{+6} using inductors with self-resonant frequencies exceeding 200 kHz. The Zener diode clamps the input to ± 15 V which provides additional spark protection.

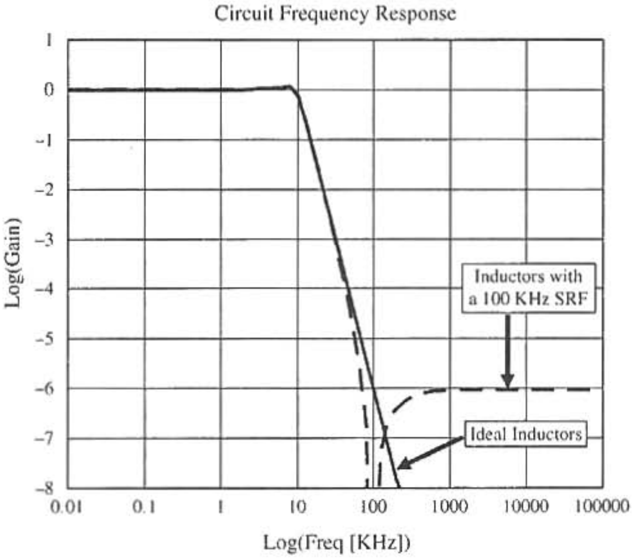

Fig. 9. Plotted is the gain as a function of frequency for the sixth order, low-pass filter shown in Fig. 8. Two cases are shown. The solid line is the gain with ideal inductors confirming that the circuit design is correct. The dashed line shows the response using real inductors with a self-resonant frequency (SRF) of 100 kHz illustrating the frequency-independent attenuation above the SRF.

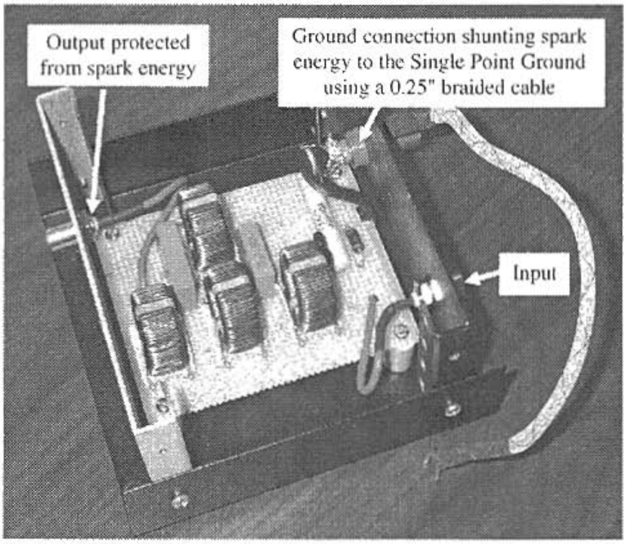

Fig. 10. The spark protection circuit is constructed using commercially available components on a vector proto-board.

isolated from case ground. This cable was connected directly to the single point ground for the experimental apparatus. This low impedance, direct connection ensures that spark energy flows directly to ground, bypassing expensive instruments.

4. Results

The gain of the spark protection circuit, measured as a function of frequency using an HP4384A Precision LCR meter, is shown in Fig. 11. The circuit was excited with a 10 mA sinusoidal current over the frequency range of 20 Hz–50 kHz. The excitation current was increased to 100 mA over frequency range 50 kHz–1 MHz where the attenuation is highest. The current in the ground leg of inductor L_3 was measured.

5. Discussion

The circuit behaves generally as designed. It is a low-pass filter with a sharp cut-off at about 10 kHz. Unity gain at low frequencies ensures that DC and low-frequency AC current measurements will be accurate.

As is evident in Fig. 11, the circuit performance deviates significantly from the intended design in several ways:

1. *Low frequency response*: The cut-off frequency, the frequency where the gain is 0.5, is 150 Hz rather than at the intended cut-off frequency of 10 kHz.

expected, the response is maximally flat, low-pass filter with a cut-off frequency of about 10 kHz.

The dashed line is the gain of the filter using real inductors with a self-resonant frequency of 100 kHz. Above the SRF, winding capacitance becomes dominate and the low-pass filter becomes a capacitive divider. As expected, the attenuation above the SRF does not vary with frequency.

3. Components and construction

3.1. Inductor self-resonant frequency

The non-ideal characteristics of the inductors determine the performance of the spark protection circuit. Inductors with high self-resonant frequencies are required for sufficient attenuation at high frequencies. However, large inductors, 10–50 mH with many windings, are required to realize low-pass filters with cut-off frequencies in the range of 1–20 kHz. The large number of windings contributes to high stray capacitance that lowers the self-resonant frequency and degrades high-frequency attenuation. Also, inductors with low DC resistance, wound with large diameter wire, are needed to provide unity gain at low frequency, so that current measurements are accurate. The large wire diameter also contributes to higher stray capacitance.

Inductors wound on toroidal, ferrite cores have the required performance. These inductors have relatively high inductance with few windings. There are two disadvantages of using toroidally wound inductors. First, they are relatively large as seen in photograph of the prototype circuit shown in Fig. 10. Also, toroidally wound inductors are susceptible to saturation of the ferrite core at high current. It is important to select inductors with a sufficiently high current rating for the application. J.W. Miller 8100 series inductors [6] are used to build the circuit shown in Fig. 10. These inductors are rated for a maximum current of several amps.

In the photograph of the circuit shown in Fig. 10, four inductors are visible whereas the design shown in Fig. 8 requires only three inductors. Two, 12 mH inductors connected in series are used for inductor L_2, the largest inductor in the circuit with a design value of 25.3 mH.

The SRF of a 12 mH, model 8111 inductor was measured using an HP4384A Precision LCR meter (20 Hz–1 MHz). The inductor was energized with a 10 mA sinusoidal current. Beginning at 20 Hz, the frequency was increased until the impedance was purely resistive (phase angle of 0°). The SRF measured approximately 650 kHz.

3.2. Circuit construction

The prototype circuit shown in Fig. 10 is built using commercially available components on a vector proto-board. A 1500 W Peak Power, Zener Transient Voltage Suppressor 1N6385 [7] clamps the input voltage to ± 15 V.

The ground connections of the diode, resistor, and three capacitors in the circuit (see Fig. 8) were connected using a low impedance, 0.25″ braided cable that is

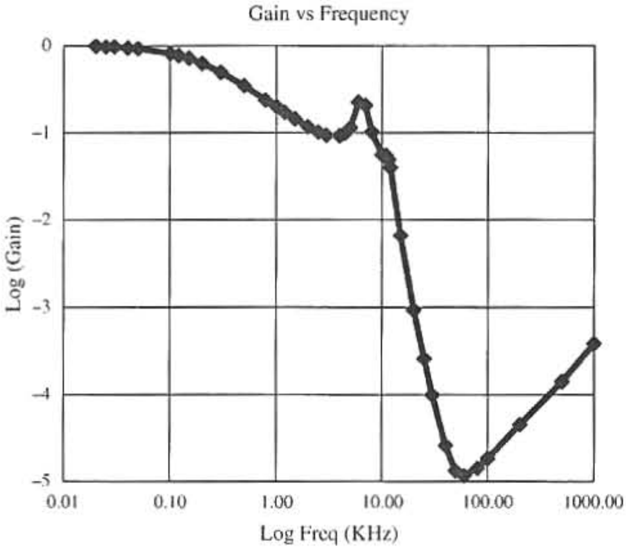

Fig. 11. Shown is the spark protection circuit gain as a function of frequency. Key features are:

(1) the low-frequency gain is unity,
(2) the maximum high frequency attenuation is about 10^{+5},
(3) the gain increases at high frequencies, and
(4) the low frequency response deviates significantly from the designed maximally flat response.

2. *Response peak at 6 kHz*: There is a peak in response at 6 kHz. The gain increases noticeably.
3. *Increasing gain above 60 kHz*: The gain increases with frequency above 60 kHz. An attenuation of about 10^{+6} that does not change with frequency is expected from the simulation results.
4. *Maximum attenuation of 10^{+5}*: The maximum attenuation is limited to about 10^{+5}. The circuit simulation predicted a high frequency attenuation of about 10^{+6}.

5.1. Low-frequency response

The gain over the range of 100 Hz–5 kHz is that of a first-order low-pass filter with a cut-off frequency of 150 Hz. The design of the circuit is a low pass filter with a cut-off frequency of 10 kHz and maximally flat low-frequency response. Although the root cause of the deviation of response from the design is unknown, it is associated with the circuit rather than the measurement apparatus and method. Two identical circuits were built and both have a first-order cut-off frequency of about 150 Hz. The circuit is designed properly as verified by the simulation results shown in Fig. 9. The circuit components were individually measured and have the proper values. The diode does not affect the frequency response of the circuit as was verified by measuring the circuit response with the diode removed from the circuit. Additional work is needed to determine the root cause of this low-frequency performance.

5.2. *Response peak at 6 kHz*

This sixth-order filter has three circuit legs that are each an LC resonant circuit. Theoretically, the resonance of one LC circuit is matched with the attenuation of another resulting in maximally flat gain at low frequency and a very abrupt decrease in gain above the cut-off frequency. Practically, high-order filters are sensitive to the circuit component values. Deviations in component values from design values result in resonances as observed in Fig. 11. For example, the design called for L_2 to be a 25.3 mH inductor. In the prototype circuit, two 12 mH inductors are connected in series to form a 24 mH inductor. This difference, together with the variations in the other components shifts the circuit performance away from the design goal. These component variations are probably responsible for the response peak at 6 kHz shown in Fig. 11.

5.3. *Increasing gain above 60 kHz*

The high frequency attenuation is critically important to protect sensitive instruments from damage by sparks. From the analysis presented in Section 2.3 the gain at high frequencies is expected to be about 10^{-6} and independent of frequency. Gain that increases with frequency above 60 kHz is unexpected. The root cause is the small, but non-zero impedance of the ground connection between the spark protection circuit and the experimental single point ground shown explicitly in Fig. 12. This circuit was simulated using the SIMPLORER® Simulation System Version 6.0 SV [5] and the results are shown in Fig. 13. Two cases are shown. When the ground resistance R_{Ground} is zero, the results are identical to the earlier results shown in Fig. 9. With $R_{\text{Ground}} = 0.1\,\Omega$, the gain increases by a factor of 10 for every decade increase in frequency above 100 kHz.

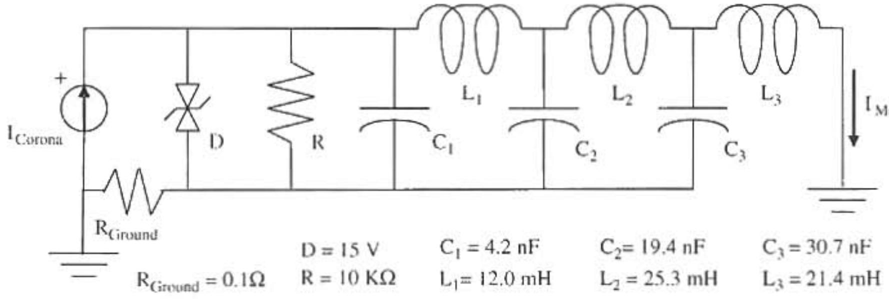

Fig. 12. The spark energy will encounter resistance R_{Ground} in the connectors and cables connecting the circuit to the experimental system single point ground.

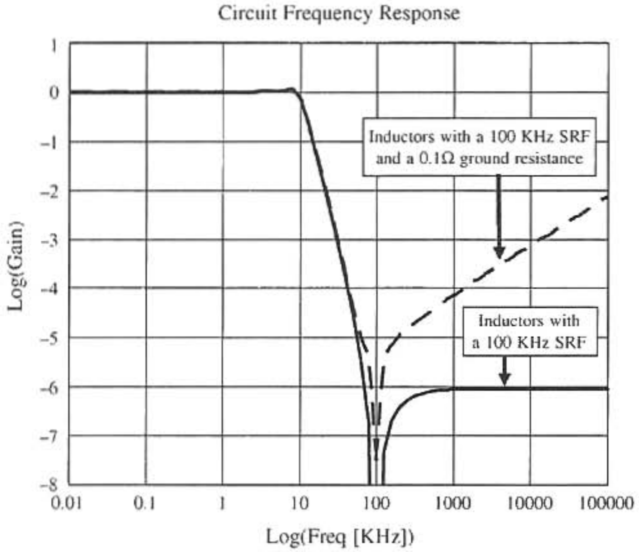

Fig. 13. Shown is the effect of the ground resistance R_{Ground} on the circuit response. The solid is the gain with $R_{\mathrm{Ground}} = 0\,\Omega$ and is consistent with earlier results. The dashed line shows the gain when $R_{\mathrm{Ground}} = 0.1\,\Omega$. For frequencies above 100 kHz, the gain increases by a decade for every decade increase in frequency.

5.4. *Maximum attenuation of 10^{+5}*

The maximum attenuation measured is about 10^{+5} whereas an attenuation of 10^{+6} is expected from the circuit simulation results. The inductors were selected carefully to have satisfactorily high self-resonant frequencies to achieve a high-frequency attenuation exceeding 10^{+6}. Above 10 kHz, the gain decreases sharply, and an attenuation of 10^{+5} is achieved at a frequency of 60 kHz. This limitation in the maximum attenuation is associated with the small, but non-zero resistance of the connection of the circuit to the experimental single point ground as discussed in the previous section.

5.5. *Circuit performance in the field*

A spark protection circuit has been built and used to protect a sensitive electrometer that monitors microampere level current during high-voltage experiments. The current flow to this electrode is monitored, as illustrated in Fig. 1 except that the spark protection circuit is inserted between the plate and the electrometer. Sparks occur regularly between a corona charger and a nearby plate electrode. Plate current is monitored reliably with no damage to the electrometer when sparks occur. Current pulses from sparks are detected by the electrometer.

The stray capacitance of the inductor windings causes the impedance of real inductors to become capacitive at frequencies above their self-resonant frequency.

This limitation is overcome using a capacitive divider strategy, as illustrated in Fig. 7. This strategy is effective because the circuit provides satisfactory protection from sparks.

There was an incident during an experiment when the spark protection circuit was inadvertently disconnected from the single point ground. A spark from the corona charger to the plate electrode damaged the electrometer. This unfortunate incident confirmed that the spark protections circuit is effective.

6. Conclusion

The sixth-order low-pass filter provides effective spark protection. Stray capacitance across the inductor windings requires additional filter stages (higher order filter) to achieve satisfactory attenuation at high frequencies. This capacitive divider strategy is effective.

The maximum attenuation is limited to about 10^{+5} and increases with frequency above 60 kHz. This high-frequency performance is caused by the small resistance of connectors and cables connecting the spark protection circuit to the experimental system single point ground.

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