

The Amplifier Input Protection Circuit for a Intraoperative Evoked Potential Monitoring System

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Abstract—In this paper a short introduction into problem of intraoperative interference will be presented. Three most important types of interferences will be analyzed. Connection between their physical properties and scheme of protection circuit will be shown. At the example of realized protection circuit we will show what are additional problems in hardware realization.

I. INTRODUCTION

Our basic intention was to make considerably quality improvement of recording of evoked potential in intraoperative environment. One of the main distinctive parameters between an ambulance and intraoperative system for evoked potentials monitoring is in the level of amplifier input protection. Input protection for intraoperative measurement ought to be much tougher regarding much higher energy levels of interference.

Quality of amplifier protection circuit basically can be described by the value of input impedance and noise. Impedance should be as large as possible while for noise opposite should stand. Unfortunately energy absorbing capability of protective components is proportionally related with their capacitance. Therefore their larger energy absorbing capability means smaller input impedance.

For the value of noise there is not such straightforward path of reasoning. Noise depends not only on type of components and their typical values but also on scheme of protection circuit. So there are lot of combinations and we have should tried some of them to find optimum with the lowest noise. After that we checked this optimal solution for interference energy level and input impedance.

It is clear that the process of amplifier protection circuit design was iterative.

II. TYPES OF INTERFERENCES

In operating room there are lot of instruments and equipments and all of them produce some level of interference. From the point of circuit protection the most important interferences are those produced by equipments directly attached on a patient body. Direct contact assures that a lot of energy can be easily transmitted between source of interference and patient body. We can make list of most common types of interferences ranked by energy content.

A. Defibrillation

Defibrillator by far poses the highest treat to amplifier electronic circuits. Its output gives high voltage long lasting pulses (5 kV, >200 ms) which means a lot of energy entering into amplifier inputs.

B. Transcranial electric stimulation

Transcranial electric stimulator is very similar to defibrillator. Both of them share similar output stage basically made of high voltage capacitor and output switch. Difference lays in the energy level of transcranial pulses. There are about order of magnitude lower than the defibrillation ones.

C. Electrosurgical device output signal

Electrosurgical device pose a different problem for amplifier protection circuit. Its output is not single pulse but relatively long (usually up to 15 seconds) interval of high frequency signal. How long will interval last depend on a surgeon decision. Output signal is of sinusoidal shape frequency between 500 kHz and 2 MHz with amplitude usually not more than 500 V. There are two basic mode of operation. In burst mode output signal is made of high repetition short lasting bursts. In continuous mode output is one uninterrupted signal interval.

III. PROTECTION PRINCIPLES

Clamping and crowbar are two basic principles of protection from over voltage. In standard circuits for amplifier protection clamping is commonly used. Such a circuit is shown on Fig. 1.

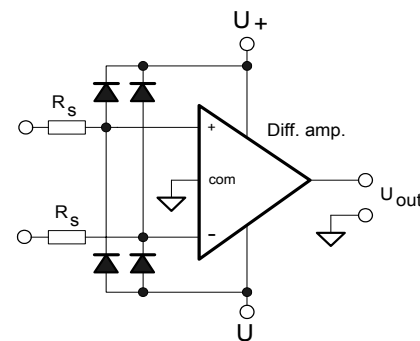


Figure 1. Standard circuits for protection of amplifier inputs.

Value of resistors R_S defines current through diodes in the presence of input voltage higher than supply voltage. How high input voltage amplitude can be depends on current capability of diodes and supply voltage source.

Parasitic capacitance of diode is larger if it can sustain larger current. Therefore preserving high input impedance means small current diodes in protection circuit and high ohmic resistors R_S .

A defibrillation proof protection circuit need resistors R_S of about 330 k Ω if we want to use a 1N4148 grade or better protection diodes. This combination is a usual choice in EKG (electrocardiograms) recorders where amplifier bandwidth is narrow. On this way high resistance value is compensated by small bandwidth in an equation for thermal noise given by:

$$E_n = \sqrt{4KT \cdot R_S \cdot BW}, \text{ V} \quad (1)$$

where E_n is root mean square value of voltage noise, K is Boltzmann's constant, T is absolute temperature and BW is noise bandwidth.

On contrast bandwidth of the amplifier for recording of evoked potentials can be as high as 20 kHz (three orders of magnitude larger than EKG). If we put this bandwidth in (1) result would be unacceptable high noise level of a protection circuit.

We can try to reduce the resistance value on the price of higher current flowing through diode. Unfortunately this reduction would be at least three orders of magnitude if it could have considerable effect on noise level. In that case we would need diodes with a current capability of tens of amperes, which have too large parasitic capacitance. On the other side such large current, which flow into power supply, poses tough problem for voltage regulation. In the case of defibrillation, energy flow through protection circuit can be much larger than the one from power supply to amplifier.

It is apparent that simple circuit from Fig. 1 cannot give required protection level while preserving low noise and high impedance on the input of amplifier. Circuit shown on Fig. 2 can do that at a price of larger complexity and price.

The circuit now has two stages of protection. On input there is a gas discharge tube, which is crowbar type of component. Its role in a protection scheme is to sink

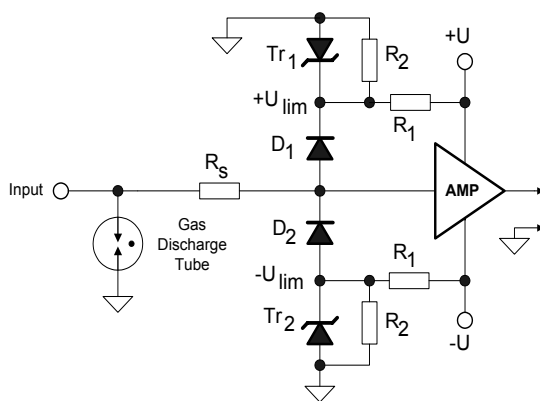


Figure 2. Circuit for amplifier input protection of a system for intraoperative evoked potentials recording.

major part of energy from input interference signal. Gas discharge tube has current sink capability of at least 5 kA (10/1000 μ s test), which is more than adequate for defibrillation protection. Moreover it has very high resistance of about 1 G Ω and capacitance is lower than 1 pF. That is in sharp contrast to all clamp types of protection components which resistance fall, and capacitance rise, very fast with current increase. Noise is also very low because gas discharge tube can be modeled, for small signal analysis, like a capacitor. Any noise comes from thermal noise of component leads, which have very low resistance.

Drawbacks of gas discharge tube are relatively slow response and sparkover voltage dependence on tube voltage rise time. Nominal sparkover voltage is valid from DC up to the rise time of about 100 V/s. After that point sparkover voltage rises to 600 V for voltage rise time of 5 kV/ μ s. This is a rule regardless of the DC sparkover voltage. So to find actual sparkover voltage it is necessary to know interference voltage rise time. If it is much higher of 100 V/s then after we divide impulse sparkover voltage (600 V) with interference risetime we could get a time of reaction. This procedure is valid only if the peak voltage of interference signal is higher than 600 V. Otherwise gas discharge tube will stay in high resistance state.

Second stage consists of resistor R_S , diodes D_1 and D_2 , unidirectional transiles Tr_1 and Tr_2 and bias resistors R_1 and R_2 . Scheme of second stage of protection is upgraded circuit from Fig. 1. Main difference is in addition of transiles, which are clamp type of components. The energy flow is diverted from power supply into them. On this way clamp voltage is much accurately known. Bias resistors define diodes and transiles reverse voltages $\pm U_{lim}$ in the absence of interferences. They have to be lower than are clamp voltages of transiles. Reason for that is that transil, which is some type of zener diode, has much lower noise out of clamp region.

From previous analysis follows that second stage of amplifier protection must be designed to sustain two cases.

- in the case of sparkover, voltage on the gas discharge tube will be in range between 15 V and 30 V. For the second stage of protection it looks like a low impedance voltage source. Therefore current that flows through second stage is ratio of voltage difference across R_S and the resistance of R_S . Since clamp voltages of transil and voltage drop on diodes are functions of their current, calculation is iterative. After few iterations we can get current in the range of several hundred miliamperes. For this current level we can choose diodes D_1 and D_2 with an average current of one ampere. Such diodes can be found with reverse capacitances smaller than 10 pF, which assures high impedance on the input.

- in the second case voltage on the gas discharge tube is not yet (or will not) reach sparkover level and the second stage has to absorb all of energy contained in an interference signal. Defibrillation and transcranial electrical stimulation induced interference have high voltage rise time and sufficiently high peak voltage to reach sparkover voltage of gas discharge tube in few microseconds. So the second stage would endure very short period of large current with peak amplitude equal to ratio between sparkover voltage of gas discharge tube (600 V) and resistance of R_S . After thorough analysis of

previously mentioned diodes D_1 and D_2 we decide to put R_S with resistance of only $100\ \Omega$ to keep noise as low as possible. Therefore peak current through resistor and diode would be $6\ \text{A}$. This current falls well into recommended conditions of chosen diodes. On contrast, resistor cannot be some standard type of bigger wattage because of current. Standard high voltage resistors have low current capability and high current types have low voltage capability. To have both on the same time we have to choose a resistors type intended for use in telecommunication industry for signal lines lightning protection.

For the case of electrosurgical unit generated interference there would be no sparkover of gas discharge tube. The reason for that is twofold. On the one hand there is a very high slew rate of voltage on gas discharge tube. On the other the signal rise direction is changing three times in one period. So in one period of interference signal there is not enough time for gas ionization regardless of signal amplitude. Gas discharge tube will stay in high impedance state and for a time interval of electrosurgical unit operation second stage of protection circuit should protect amplifier input. From the datasheets we could find that continuous average current for diodes is $1\ \text{A}$. Since each diode conducts only one half of a period, peak current would be $3.14\ \text{A}$. This means that continuously allowable interference amplitude can be $314\ \text{V}$. This is two thirds of the amplitude on the output of electrosurgical unit. Therefore it seems that direct contact between knife and input of amplifier would be catastrophic event. It is not the case because there is the impedance of a patient body between neutral electrode of amplifier and neutral electrode of electrosurgical unit. This impedance is something about $100\ \Omega$ typically, which is enough to limit the current through diodes on safe level.

IV. SMALL SIGNAL ANALYSIS

Scheme for small signal analysis is shown on Fig. 3. Because of reverse polarization of diodes and transiles only their capacitances where taken into account. Typical values for C_{Tr} and C_D are $5\ \text{nF}$ and $5\ \text{pF}$. Also shot noise of diodes and trasiles can be calculated by:

$$I_N = \sqrt{2q \cdot I_D}, \text{ A}/\sqrt{\text{Hz}} \quad (2)$$

where I_N is noise current density, q is electron's charge, I_D is current through diode or transil.

Currents I_D through diodes D_1 and D_2 are small because reverse polarization and have values of $20\ \text{nA}$. From (2) we get their noise of $0.08\ \text{pA}/\sqrt{\text{Hz}}$. Currents I_D through transiles are much bigger and have values of $120\ \mu\text{A}$. Noise is now $6.2\ \text{pA}/\sqrt{\text{Hz}}$. This is two orders of magnitude bigger then the previous case. This could be a problem but after inspection of the scheme we can see that very large impedances of reverse polarized diodes stay between transiles and input of amplifier. Therefore transil's noise contribution to noise of protection circuit can be neglected regardless of electrode impedance.

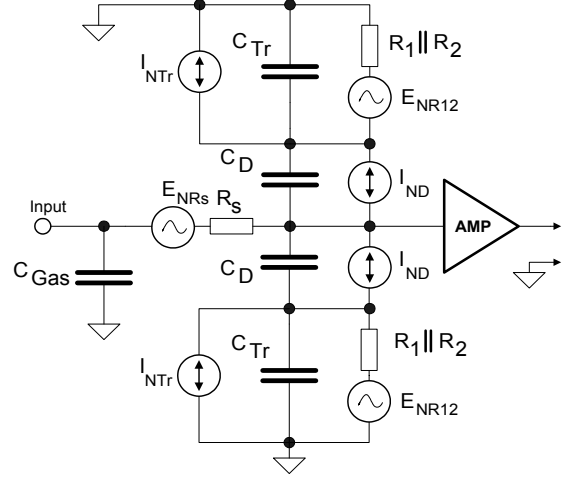


Figure 3. Small signal scheme of the amplifier protection circuit.

Noise contribution of diodes depends on electrode impedance. Electrode impedance range is between $1\ \text{k}\Omega$ and $20\ \text{k}\Omega$. Noise contribution of diodes for electrode impedance of $1\ \text{k}\Omega$ is too low and practically there is only thermal noise of resistor R_S (1) of $1.3\ \text{nV}/\sqrt{\text{Hz}}$. For electrode impedance of $20\ \text{k}\Omega$ situation is opposite. Noise is defined by two diodes and has the value of $3.3\ \text{nV}/\sqrt{\text{Hz}}$. For intraoperative applications there are special types of electrodes (corck screw) with small effective surface. Their capacitances are therefore small and we can suppose than electrodes impedance is pure resistance. Now we can put noise of protection circuit in perspective with noise of electrode. For electrode resistances of $1\ \text{k}\Omega$ and $20\ \text{k}\Omega$ we can get thermal noise (1) of $4\ \text{nV}/\sqrt{\text{Hz}}$ and $18\ \text{nV}/\sqrt{\text{Hz}}$. These values are at least three times greater of protection circuit ones. So we can conclude that protection circuit will not raise significantly noise level at the input of amplifier.

How the protection circuit affect input impedance is clear from Fig. 3. A capacitance of series connection of capacitances of diodes and transiles is equal to diode's since of its much smaller value. So protection circuit adds two diode's capacitances and capacitance of gas discharge tube to an amplifier input capacitance.

V. REALIZATION

In realization of protection circuit main problem was small volume, which we could assure for circuit placement. Fig. 4 shows how protection circuit components are placed on two printed circuit boards. Third printed circuit board, placed on the left side of the module, is amplifier input.

The smallest circuit board is reserved for electrode socket connection and gas discharge tube placement. Main problem here was realization of creepage distances among components and connection pads. Also it is important to note that montage fixture do not have just mechanical purpose. It is also means of realization a low impedance path to neutral electrode.

On the bigger board the rest of protection circuit is placed. Thin white plate on board is resistor R_S . Here, a problem of montage of resistor R_S made creepage distances solving more difficult.



Figure 4. Picture of realized protection circuits.

VI. MEASUREMENTS

Input protection circuit was tested in operating room several times during a surgical procedure on a brain tumor. An electrosurgical device and a transcranial magnetic stimulator were used in procedures. Output frequency of an electrosurgical device was 1 MHz and amplitude of no more than 500 V. Electrodes were placed on a head about 10 cm from tumor. Protection circuits protected input of the amplifiers from effects from both devices without any problem.

Measurement of input impedance showed that real part of it has value from 1.2 G Ω to 1.3 G Ω . Imaginary part is capacitive and has value from 21 pF to 28 pF. So the

module of impedance on 50 Hz is between 113 M Ω and 150 M Ω . This is good result in comparison with the maximum allowable electrode impedance of 20 k Ω .

Voltage noise densities of protection circuit are 1.28 nV/ $\sqrt{\text{Hz}}$ and 3.6 nV/ $\sqrt{\text{Hz}}$ for input resistances of 1 k Ω and 20 k Ω .

VII. CONCLUSION

Preliminary measurements with realized equipment show good agreement with predicted performance parameters. For now we have made measurements with electrosurgical unit and transcranial magnetic stimulator. Measurement of input capacitance of amplifier and protection circuit shows that its value is around 25 pF. Additional capacitance comes from PCB traces, wires and electrode cable socket. Such low value of capacitance gives high rejection of interferences.

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