On the Reduction of Interference Due to Common Mode Voltage in Biopotential Amplifiers

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***Abstract*—In this paper, work done, on the reduction of interference due to common mode voltage in biopotential amplifiers, in two papers authored by B.B. Winter and J.G. Webster [1], and R. Pallas-Areny [2] is summarized and approaches to solve the problem are compared with each other. Several aspects on nonidealities of amplifiers and models described by the authors are discussed.**

I. Introduction

ECG, EEG, and EMG are some examples of biopotential signals. Since these signals are obtained from body sources, it is tricky to get higher amplitudes and pure signal. Thus, interference and noise are two very important topics on this subject. If not handled well, it can cause hard interpretations of the signal, and even false diagnosis in some cases. Interference originates from power sources around, and interference of the recording can happen in many situations. 1) A magnetic field induces a voltage in the loops formed by the cables of electrodes, which can be decreased by simply twisting the cables and decreasing the loop area. 2) An electric field creates a displacement current into the electrodes, which can be decreased by shielding the cable. 3) An electric field creates a displacement current into the body, which can be decreased by accurate electrode positioning. 4) A voltage is created due to this induced current between the leads and the amplifier common, which is called common mode voltage, v_c. Common mode voltage interferes the signal only if there are nonidealities and mismatches of the components of the biopotential amplifier, which is always the case. When there is an interference due to common mode voltage, what do we do? Both Winter and Webster [1], and Pallas-Areny [2] have tried to solve this particular problem and suggest their solutions on the reduction of interference due to common mode voltage in biopotential amplifiers.

In [1], the authors examine nonideal behaviour of amplifiers and how it leads to an interference. Information about common mode voltage and its components, power line induced ac voltage and static voltage, is given and a model is presented for the common mode voltage on the body. Some other questions such as what are the sources of common mode voltage, what can cause higher common mode voltage, and what are the typical values of its components are answered. Effective common mode rejection ratio, $\mathrm{CMRR_e}$, is defined and it is stated that to reduce the interference, $\mathrm{CMRR_e}$ should be increased. Its terms and effects of these terms on $\mathrm{CMRR_e}$ are analyzed. Furthermore, the authors review interference reduction in nonisolated and isolated amplifiers, both two and three electrodes. Optimal component calculations and effects of static voltage are shown in those amplifiers. Conclusions made by these authors to reduce the interference are to increase $\mathrm{CMRR_e}$ and isolation of the amplifier.

In [2], R. Pallas-Areny restates the conclusions of B.B. Winter and J.G. Webster [1] and claims the model presented by these authors are not a complete model, and this model lacks an important aspect, which is that there is also a voltage drop that causes errors in isolation part. After reviewing the material for both nonisolated and isolated amplifiers, a more complete model is described for isolated case. Isolation mode rejection ratio, IMRR, is defined for ground-reference isolated amplifiers, and it is stated that to reduce the interference, a low common mode impedance and a high isolation mode impedance is optimum.

II. Summary of [1]

In [1], first the authors describe how common voltage is converted to a differential one, then they show how the interference can be reduced in biopotential amplifiers.

A. Common Mode Voltage

As mentioned before, common mode voltage, v_c, consists of power line induced ac voltage, v_a, and static voltage, v_s, as given in Equation 1.

$$v_c = v_a + v_s \tag{1}$$

Displacement current going through stray capacitances creates power line induced ac voltage. It depends the distance between the patient and power sources (or grounded objects). It could be high as $20\mathrm{V}$ when the patient holds a power cord or low as a few milivolts when the patient is in touch with a grounded object, it is usually around $1\mathrm{V}$. For static voltage, it depends the movements, body-ground capacitances charges with static electricity, which induces a voltage. This voltage may change the baseline or lead to saturation.

B. Effective Common Mode Rejection Ratio

Interfering voltage, v_i, can be written as in Equation 2.

$$v_i = v_c \underbrace{(1/\text{CMRR}}_{\text{1st term}} + \underbrace{Z_d/Z_c}_{\text{2nd term}}) \tag{2}$$

where Z_d, difference between the electrode impedances
Z_c, common mode impedance
CMRR, differential gain/common mode gain

Normally, very high values for CMRR is desired, however it is usually between $60-120$ dB. Also, second term in Equation 2 is originated from voltage division of input impedance to impedance of stray capacitances when there is a difference between Z_1 and Z_2, which is Z_d. Its effect is similar to CMRR, so the authors define effective common mode rejection ratio as in Equation 3.

$$1/\text{CMRR}_\text{e} = (1/\text{CMRR} + Z_d/Z_c) \tag{3}$$

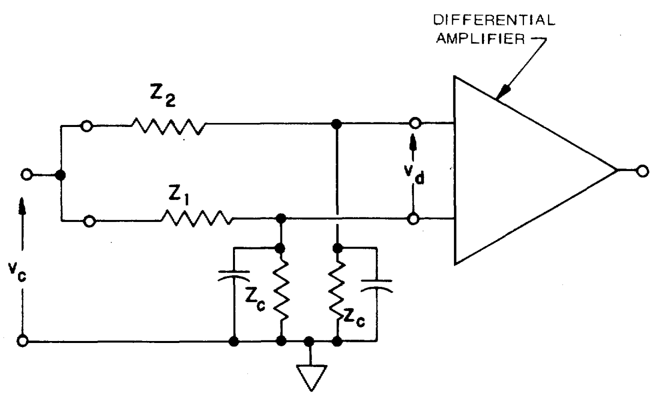

Fig. 1: Common mode voltage can be transformed into a differential voltage if the electrode impedances are imbalanced.

C. Interference Reduction in Nonisolated Amplifiers

Their proposal to reduce the interference is either to increase CMRR_e or to add a third electrode to reduce common mode voltage.

1) Two-Electrode Amplifiers: In this part, the authors review a two-electrode amplifier by Thakor and Webster [3] shown in Figure 2.

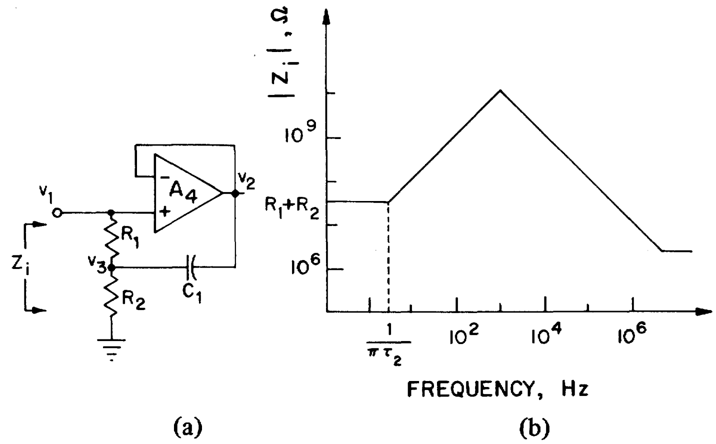

Fig. 2: (a) Circuit diagram of a high input impedance bootstrap input buffer that provides input bias current to A_4 through R_1 and R_2. v_1 connects to the patient. v_2 drives the rest of the amplifier. (b) Input impedance of the buffer as a function of frequency.

They conclude that it gives a high input impedance and input bias current is provided by the body of the patient. They calculate input impedance as

$$Z_i = \frac{[R_1(1+\tau_1 s) + R_2](1 + 1/G_o + s\tau_a/G_o)}{s^2\tau_1\tau_a/G_o + s(\tau_1+\tau_a)/G_o + 1 + 1/G_o} \tag{4}$$

where

$\tau_a = 1/(2\pi f_a)$, f_a, corner frequency of opamp
$\tau_1 = R_2 C_1$, G_o, opamp's open loop gain

Then, it is further simplified by assuming bipolar amplifiers are not used and the frequency is below $G_o/(\tau_1+\tau_a)$ and $[G_o/\tau_1\tau_a]^{1/2}$ as

$$Z_i = R_1R_2C_1s + (R_1+R_2) \tag{5}$$

After that an equivalent circuit is presented and time constant of the circuit, which have a suitable value, is calculated as

$$\tau = 2R_1R_2C_1/(R_1+R_2) \tag{6}$$

All the component values are chosen such that it increases CMRR_e by increasing the common mode impedance.

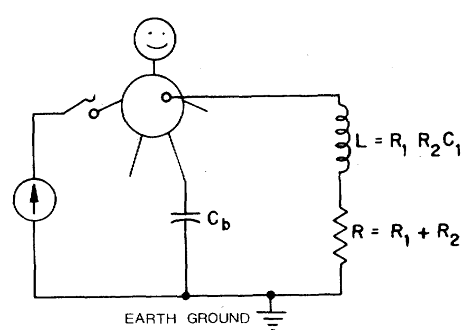

Fig. 3: Equivalent circuit of the buffer when it is coupled to a body that is charged to a static voltage. C_b is the body capacitance to earth ground.

2) Three-Electrode Amplifiers: Another way is to reduce v_c by adding a third electrode. Aim of adding third electrode is to create a low impedance path for displacement current to ground, since the patient cannot be connected to the ground directly as it is not safe. Most efficient way to achieve this is not mentioned in their paper, but it is claimed that it is the driven-right-leg circuit [4]. They provide a simple grounding circuit consists of a diode configuration shown in Figure 4.

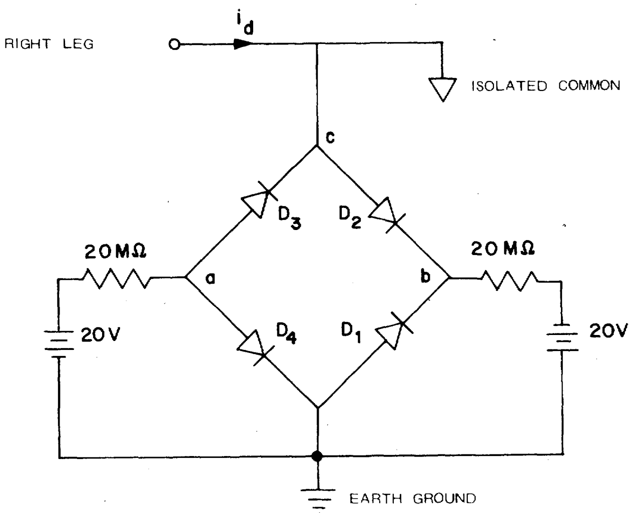

Fig. 4: A simple grounding circuit that provides a low-impedance path to ground for currents less than $1\mu A$ and a high impedance to ground for currents greater than $1\mu A$.

D. *Interference Reduction in Isolated Amplifiers*

Most amplifiers use isolation to protect the patients from the flow of high currents into their bodies.

1) Two-Electrode Amplifiers: For two-electrode amplifiers, it is done by putting an isolation impedance, shown in Figure 5.

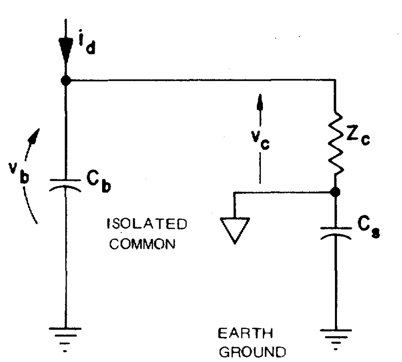

Fig. 5: The common mode voltage in isolated amplifiers can be reduced by reducing Z_c or by increasing Z_s.

Common mode voltage can be calculated from Figure 5 as in Equation 7.

$$v_c = v_b \left[Z_c / \left(Z_s + Z_c \right) \right] \doteq v_b Z_c / Z_s \tag{7}$$

v_b, body voltage with respect to earth ground

By putting in Equation 2, we get

$$v_i = \left(v_b Z_c / Z_s \right) \left(1/\mathrm{CMRR} + Z_d / Z_c \right) \tag{8}$$

So, we can reduce interfering signal by decreasing Z_c and by increasing Z_s. However, decreasing Z_c is not effective if there is a huge difference in electrode impedances. Increasing Z_s, that is to say decreasing C_s is more effective.

2) Three-Electrode Amplifiers: Decreasing C_s can be done with negative capacity amplifier, however there is a limit such as a few picofarads. Thus, the authors say we need a third electrode to the isolated common to further decrease the common mode voltage by lowering effective impedance by using a driven-right leg circuit.

Lastly, they review another circuit from Hewlett-Packard Corporation [5] to clarify their other paper about driven-right-leg circuit [4].

III. Summary of [2]

In [2], first the author reviews two-electrode isolated and nonisolated amplifiers by claiming that there are some flaws and exaggerated assumptions in [1], then he presents a model for isolated biopotential amplifiers and defines IMRR, isolation mode rejection ratio.

A. *Interference Reduction in Nonisolated Amplifiers*

R. Pallas-Areny gives bootstrap input buffer as an example of a nonisolated biopotential amplifier as Winter and Webster did in [1] and states its input impedance and time constant. For convenience, equations and figure are shown again in Equation 9, and 10 and Figure 6.

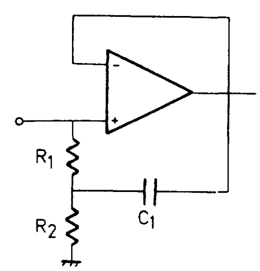

Fig. 6: Circuit diagram of a high input impedance bootstrap input buffer

$$Z_i = R_1 R_2 C_1 s + \left(R_1 + R_2 \right) \tag{9}$$

$$\tau = 2 R_1 R_2 C_1 / \left(R_1 + R_2 \right) \tag{10}$$

For a given set of CMRR, Z_i, v_c, Z_d, τ, and C_1, Winter and Webster [1] suggested that

$$R_1 = 50\mathrm{M}\Omega, R_2 = 50\mathrm{k}\Omega$$

The author claims that it never works in real applications by two reasons. 1) Equation 9 is only applicable when the input impedance of the amplifier is very high, which is never possible since such low input capacitances is unreachable (at that time of course). 2) For the worst case scenario, a great difference in electrode impedances and when a high CMRR is needed, i.e. the signal is an EEG signal, a huge input impedance must be obtained, which is again impossible for poor quality components and thermal noise.

B. Interference Reduction in Isolated Amplifiers

Another topic that Winter and Webster [1] was not careful about is that an isolation amplifier not only rejects common mode voltage but also isolation mode voltage, Pallas-Areny states.

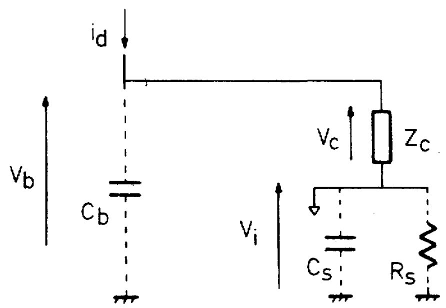

Fig. 7: The voltage on the body v_b results in common mode and isolation mode voltages v_c and v_i

Thus, the author gives a more complete model shown in Figure 7, and derives the required equations again. For an isolated voltage, v_i, interfering signal, v_n is obtained as

$$v_n = v_c\left(1/\mathrm{CMRR} + Z_d/Z_c\right) + v_i/\mathrm{IMRR} \tag{11}$$

Common mode voltage and isolated mode voltage is found as

$$v_c = i_d \frac{Z_b Z_c}{Z_b + Z_c + Z_s} \tag{12}$$

$$v_i = i_d \frac{Z_b Z_s}{Z_b + Z_c + Z_s} \tag{13}$$

By putting v_c and v_i from Equations 12 and 13 to Equation 11, we get

$$v_n = i_d \frac{Z_b}{Z_b + Z_c + Z_s}\left(\frac{Z_c}{\mathrm{CMRR}} + Z_d + \frac{Z_s}{\mathrm{IMRR}}\right) \tag{14}$$

Z_{CE} can be interpreted as an effective coupling impedance, and defined by

$$Z_{CE} = \frac{Z_b}{Z_b + Z_c + Z_s}\left(\frac{Z_c}{\mathrm{CMRR}} + Z_d + \frac{Z_s}{\mathrm{IMRR}}\right) \tag{15}$$

Reduction of interference due to common voltage can be done by reducing this effective coupling impedance, which can be possible by adjusting Z_c and Z_s accordingly. CMRR and IMRR play an important role here.

In Figure 8, effective coupling impedance is shown with respect to Z_c and Z_s. For $\mathrm{CMRR} < \mathrm{IMRR}$, which is the case most of the time, increasing Z_s leads to a better solution. For Z_c, the author states that we need to take the derivative and see that it changes sign when

$$Z_s = \frac{\mathrm{IMRR}\left(\mathrm{CMRR}\cdot Z_d - Z_b\right)}{\mathrm{IMRR} - \mathrm{CMRR}} = Z_{sl} \tag{16}$$

By interpretation of this results, the author states decreasing Z_c leads to a better solution most of the time. By looking to the Equation 15, it can be observed that there are infinitely many solutions, however there is an permissible region for (Z_c, Z_s).

To conclude, it does not matter if it is two-electrode or three-electrode amplifier, isolation barrier error should be taken into account. In both cases, effective coupling impedance should be reduced. As a rule of thumb, for high isolation impedance and high IMRR, reduction of Z_c results in reduction in effective coupling impedance, Z_{CE}.

IV. Comparison of [1] and [2]

In this section, based on what is summarized in Section II and III, the advantages and disadvantages of the approaches in [1] and [2] will be discussed. First of all, we should understand the similarities and differences of the approaches in these papers.

While Winter and Webster [1] focus on the voltage drop in common mode impedance, and almost never mention about the isolation impedance, Pallas-Areny discusses its presence and effects deeply. Main reason why Winter and Webster do not pay no attention on this aspect of the common mode reduction is that the importance of the isolation capacitance is somewhat a huge topic when driven-right-leg circuit is used [4], and here it does not need much attention. On the other hand, Pallas-Areny [2] puts emphasis on isolated mode voltage and its importance on interfering voltage. We clearly see that what is missing when Equations 17 and 18 are compared.

$$v_n = v_c\left(1/\mathrm{CMRR} + Z_d/Z_c\right) \tag{17}$$

$$v_n = v_c\left(1/\mathrm{CMRR} + Z_d/Z_c\right) + v_i/\mathrm{IMRR} \tag{18}$$

In fact, it will be equally effective in each model when appropriate ambient conditions occur, which is high input impedance for amplifier and a higher precision so that the worst case scenario never occurs. That is, building a more complicated model as in [2] may not always be necessary. If I have to say, Pallas-Areny was right to say those assumptions were hard to achieve at that time. However, those assumptions can be used for today's circuits, which indicates that both models are equally effective nowadays.

All in all, Winter and Webster [1] neglect the isolation impedance in their computations assuming it will not be that effective in every situation and simplify their results, which is advantageous as it provides a higher understanding of the topic by easing the computations. Going into further details complicates the topic way more and the aim of the paper [1] is to arrive driven-right-leg circuit, where stray capacitances have a different importance. Conversely, Pallas-Areny goes into details to find the optimal solution for the interference. For different values of isolation impedances, which was assumed infinity in Winter and Webster [1], effect of common mode

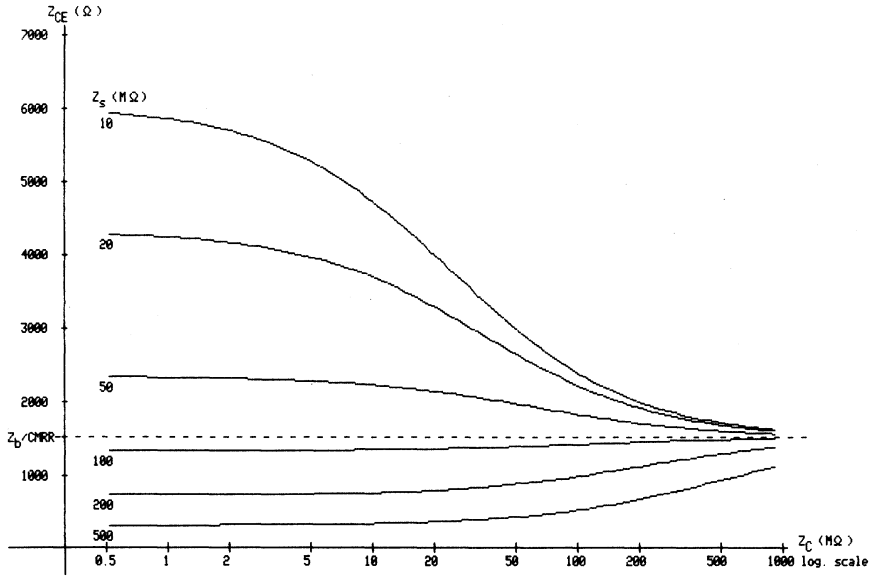

Fig. 8: Effective coupling impedance (Z_{CE}) as a function of common mode (Z_c) and isolation mode (Z_s) impedances

impedance are examined. Pallas-Areny shows in some situations increasing common mode impedance leads to a better performance, contrary to what Winter and Webster stated.

V. Discussion

Now, since we know how the interference occurs and not only common mode impedance but also isolation impedance affects the interference, we can discuss other ways to reduce the interference of the common mode voltage. One remarkable way to introduce a third electrode and create a low impedance path for displacement current. This third electrode cannot be utilized directly since it is dangerous for the patient and also a high impedance can occur with poor electrode contact, thus the driven-right-leg circuit is presented in [4], which I want to discuss the circuit and principles. The right leg is connected to the output of an auxiliary opamp, shown in Figure 9. Governing equations are given as follows

$$v_o = -Gv_c, \quad G = 2R_f/R_a \tag{19}$$

$$v_o = v_c - (R_o + R_{e1})\, i_{d_2} \tag{20}$$

$$v_c = R_c i_{d2}, \quad R_c = (R_o + R_{e_1})/(G+1) \tag{21}$$

$$i_d = \frac{v_c - v_{cc}}{R_o + R_{e_1}} \approx \frac{220}{R_o + R_{e_1}} \tag{22}$$

Common mode voltage can be reducing the effective resistance to common, by choosing small R_a and large R_f and R_o. For further discussion of the stability of the circuit, one can look at the paper "Driven-Right-Leg Circuit Design", [4]. Advantages of this circuit is obvious when it comes to design, especially it is relaxing to know that the safety of the patient and the flexibility of the range for the components are assured.

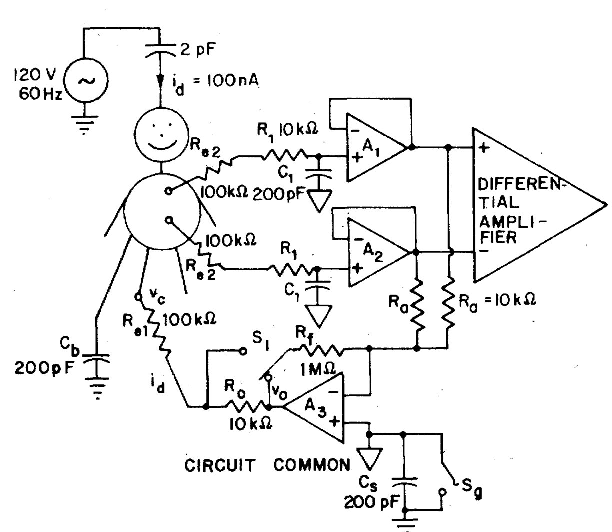

Fig. 9: A typical driven-right-leg circuit. A_3 drives v_c. to a small value.With switch S_g open, the circuit represents an isolated amplifier with a stray capacitance to earth ground of C_s. C_b is the capacitance between the body and earth ground.

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