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ORIGINAL ARTICLE

Estimation of stray coupling capacitances in biopotential measurements

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Abstract Biopotential measurements are very sensitive to electromagnetic interference (EMI) from power-lines. Interference conditions are mainly imposed by electric-field coupling, whose effects can be described by coupling capacitances. The main of them are the patient-to-ground and the patient-to-power-line capacitances, usually denoted as C_B and C_P, respectively. A technique to estimate these elements and experimental data obtained in different environmental conditions are presented. It was found that C_B ranges from hundreds of pF to nF, and C_P from hundredths of pF to few pF. The presented technique also lets it know the small amplifier-to-ground and amplifier-to-power-line capacitances. The knowledge of all these capacitances allows estimating the EMI conditions that biopotential amplifiers can be subject to, thus, resulting useful data for specifying their design requirements and constraints in real working conditions.

Keywords Power-line interference · Stray coupling capacitance · Electric-field interference · Biopotential amplifiers

1 Introduction

Biopotential acquisition equipments have left medical rooms to work in domestic environments. Holter systems, as current wearable monitoring devices, must be able to work in very aggressive interference environments. The knowledge of the EMI conditions that biopotential amplifiers can be subject to, is particularly important for designing these portable devices; in order to obtain interference-free biomedical signals [6] and to prevent amplifier saturation because of high EMI levels [2, 4].

The effects of electric-field power line interference in biopotential measurements can be described by stray coupling capacitances between the patient's body and the biopotential amplifier to the power line and ground [5, 6]. While typical values for these capacitances can be found in the literature [6, 13], a measurement technique to estimate its values for different real conditions and environments is presented. It allows predicting common mode interference levels and also provides useful information for biopotential amplifier [3, 9] and Driven Right Leg circuit designs [11–13].

There are a few methods to estimate coupling capacitances in biopotential measurements [1, 7], but they are not appropriate for low capacitance values as that associated to small battery-powered devices. The proposed method resolves values of capacitances to power line of hundredths of pF and capacitances from body or amplifier to ground as low as a few pF.

2 Methods

The electric-field power line interference can be described by the equivalent circuit of Fig. 1a, where couplings are represented by the capacitances C_P, C_B, C_{SUP}, and C_{ISO} [5, 6], which impose a common mode voltage V_{CM} on the third electrode's impedance Z_{E3}. The last two capacitances, which depend on amplifier's features as power supply

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isolation and amplifier size, can be minimized by design, but C_P and C_B depend on less controllable factors, as patient area and his/her distance to grounded objects and to power cords.

The methods to estimate C_P and C_B [1, 7] rely on connecting a variable load resistor R_L in parallel with the patient and measuring the voltage V_L on this resistor as Fig. 1b shows. This voltage is given by:

$$|V_L| = \frac{V_{PL} 2\pi f_{PL} C_P R_L}{\sqrt{1 + (2\pi f_{PL}(C_P + C_B)R_L)^2}} \tag{1}$$

where f_{PL} is the power line frequency (50/60 Hz), and V_{PL} the power line voltage (220/110 V). In the calculus of voltages and impedances, $f_{PL} = 50$ Hz and $V_{PL} = 220$ V will be assumed.

Some typical curves for (1) are shown in Fig. 3. They present two asymptotes. For low R_L values, V_L only depends on C_P as:

$$\text{for } R_L \to 0 \quad |V_L| \cong V_{PL} 2\pi f_{PL} C_P R_L \tag{2}$$

On the other hand, for high R_L values, V_L tends to:

$$\text{for } R_L \to \infty \quad |V_L| \cong V_{PL} \frac{1}{1 + C_B/C_P}, \tag{3}$$

Therefore, obtaining C_P from (2) and replacing it in (3), is possible to find C_B. The curve corner is for R_{LC} given by:

$$R_{LC} \cong \frac{1}{2\pi f_{PL} C_B} \tag{4}$$

It is important to note that, in order to estimate both C_P and C_B with a good sensibility, V_L measurements for R_L well below and above R_{LC} are required. If all the measurements correspond to low R_L values, only C_P can be accurately estimated. On the other hand, if all of them correspond to high R_L values, just the relationship C_B/C_P can be found. Considering $C_B = 100$ pF, a R_{LC} of around 30 MΩ results, calling for R_L values ranging from a few MΩ to hundreds of MΩ. The same method can be applied to estimate C_{SUP} and C_{ISO} just replacing the patient in Fig. 1b by the amplifier's ground plane but, given that C_{ISO} can be as low as few tens of pF, R_L of the order of GΩ are required. Another limitation is imposed by the stray capacitances in parallel with R_L (denoted as C_L in Fig. 1b). They are mainly due to cable capacitances and limits the minimum measurable capacitance.

The technique proposed in [7] provides a good and easy way to estimate C_P and C_B by just using an oscilloscope probe but, given that in this case R_L is limited to 10 MΩ, its sensitivity decays for low C_B values. In this article, a technique that achieves R_L values ranging from cents of kΩ to few GΩ is presented, which permits to measure C_B and C_{ISO} capacitances as low as tens of pF.

2.1 Instrumentation

The proposed experimental setup to estimate the stray capacitances is shown in Fig. 2. It uses eight switches to select different R_L values. Single resistors were used for the four lowest values ranging from 500 kΩ to 10 MΩ, and a bootstrap topology [8] to simulate high value resistors R_L. Assuming an infinite loop gain and input impedance of the operational amplifier, the equivalent R_L value results:

$$R_L \cong R_1 + R_2 + R_1 \frac{R_2}{R_3} \tag{5}$$

Using $R_1 = 5$ MΩ, $R_3 = 100$ kΩ and R_2 ranging from 1 to 20 MΩ, R_L varies from 50 MΩ to 1GΩ. The circuit was implemented using the operational amplifier OPA129 of Texas Instruments, which present an ultra high input impedance and low bias current. It also includes a shield driver circuit [10] to avoid the effects of shielded-cable capacitances and a band-pass filter to remove DC bias and to select the power-line component of V_L. This filter allows using a simple "true-rms" multimeter for the measurements.

The values of the stray coupling capacitance are estimated by fitting the theoretical curve given by (1) to the

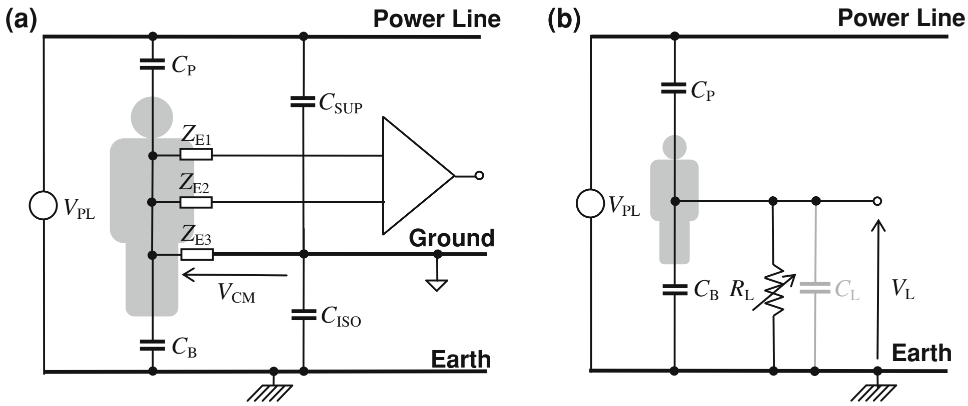

Fig. 1 **a** A classic model for power-line electric field interference. **b** General scheme for the measurement of coupling capacitances

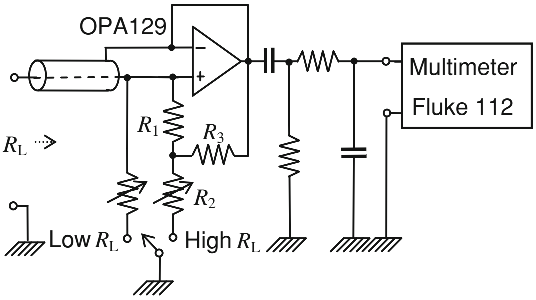

Fig. 2 Experimental setup used for stray capacitance measurements

experimental data. The estimated capacitances are those that provide the best matching of expression (1) with the experimental measurements in a Minimum Mean Square Error (MMSE) sense.

The proposed technique was employed to estimate the patient (C_B, C_P) and amplifier capacitances (C_{SUP}, C_{ISO}) for typical measuring conditions. Several tests were performed varying patient position, EMI environment, and biomedical equipment.

3 Results

3.1 Estimation of patient capacitances

The stray coupling capacitances to the patient were estimated for different conditions resulting in the experimental data summarized in Table 1. It can be observed that the patient-ground capacitances C_B generally ranges from 100 to 200 pF depending on his/her contact with the earth (shoes sole, feet on earth or feet raised); but it significantly increases with the patient's effective area. In this way, it increases to around 300 pF when he/she touches a desk or when he/she is touched by another person, reaching several nF when the patient touches a large object (e.g., a locker). About the power line-patient capacitance C_P, it strongly depends on the proximity to energy cables and main-powered objects. It can be as low as hundredths of pF when the patient is in the middle of a room, increasing to several pF when he/she touches a wall switch. Some experimental data are presented in Fig. 3 showing a good agreement with the theoretical curves given by (1), thus, validating the simple EMI model of Fig. 1a. Table 1 also includes the expected V_{CM} voltage (it is the voltage across the third electrode impedance (Z_{E3}) in Fig. 1a), for the two kinds of biopotential acquisition systems which will be presented later: a multichannel main-powered system ($C_{SUP} = 3.3$ pF, $C_{ISO} = 99$ pF) and a small battery-powered device ($C_{SUP} = 0.03$ pF, $C_{ISO} = 29$ pF). For the calculus of V_{CM}, as in [7], a third electrode resistive impedance, $Z_{E3} = 100$ kΩ was assumed. The common mode voltage was calculated solving the circuit of Fig. 1a, resulting in (6). It shows how the common mode voltage V_{CM} depends on all the involved capacitances.

$$V_{CM} = \frac{V_{PL} \cdot \left| \frac{C_P}{C_P + C_B} - \frac{C_{SUP}}{C_{SUP} + C_{ISO}} \right| \cdot Z_{E3}}{\sqrt{\left[\left(\frac{1}{C_P + C_B} + \frac{1}{C_{SUP} + C_{ISO}} \right) \frac{1}{2\pi f_{PL}} \right]^2 + Z_{E3}^2}} \qquad (6)$$

3.2 Estimation of amplifier's capacitances (C_{ISO}, C_{SUP})

The proposed technique was employed to estimate stray coupling capacitances of some biopotential acquisition systems, resulting in the experimental data of Fig. 4 that are summarized in Table 2. For a multichannel system,

Table 1 Coupling capacitances C_P and C_B for different patient conditions and expected common mode voltages V_{CM} for two typical acquisition systems: (A) multichannel, main-powered and (B) small battery-powered device

#	Patient condition	C_B (pF)	C_P (pF)	V_{CM} (mV) (A)	V_{CM} (mV) (B)
1	Standing in the middle of the room	177	0.06	14.3	0.2
2	Standing close to a lamp	145	1.53	9.1	1.0
3	Standing close to a lamp and touching the switch	145	2.80	5.5	2.0
4	Standing close to a wall switch	143	0.15	12.9	0.1
5	Standing and touching a wall switch	136	1.76	7.9	1.2
6	Standing and touching a metallic locker	3932	1.90	22.0	0.2
7	Sitting in the middle of the room with feet on earth	190	0.07	14.7	0.2
8	Sitting in the middle of the room with feet up	116	0.07	11.9	0.1
9	Sitting at a computer (desk) and using a mouse	224	0.47	14.7	0.0
10	Sitting with a standing person close to the patient	154	0.84	11.4	0.4
11	Sitting with a standing person touching the patient	273	2.06	12.8	0.7
12	Standing person in #10 and #11 (close to a desk lamp)	224	1.87	11.7	0.8
13	Sitting close to a lamp, one foot on earth	121	2.06	6.1	1.7
14	Sitting close to a lamp, feet on earth	158	2.04	8.4	1.3

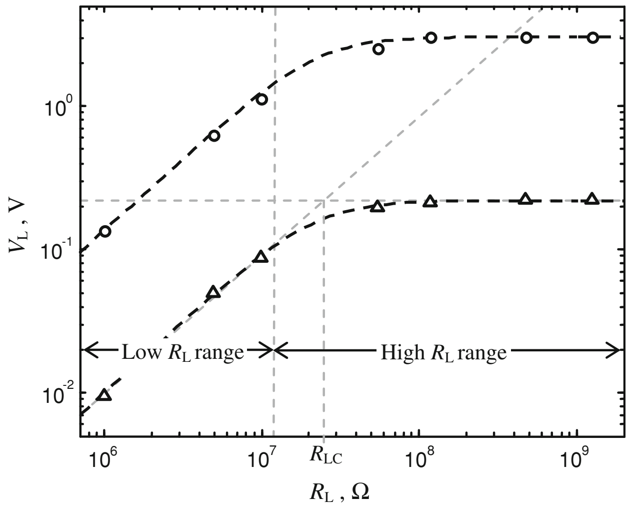

Fig. 3 Experimental measurements of patient's capacitances. Standing close to a wall switch (case 4 in Table 1) (*triangles*), standing and touching a wall switch (case 5 in Table 1) (*circles*). The *curves* in *dashed line* correspond to Eq. 1 for the estimated C_P, C_B values

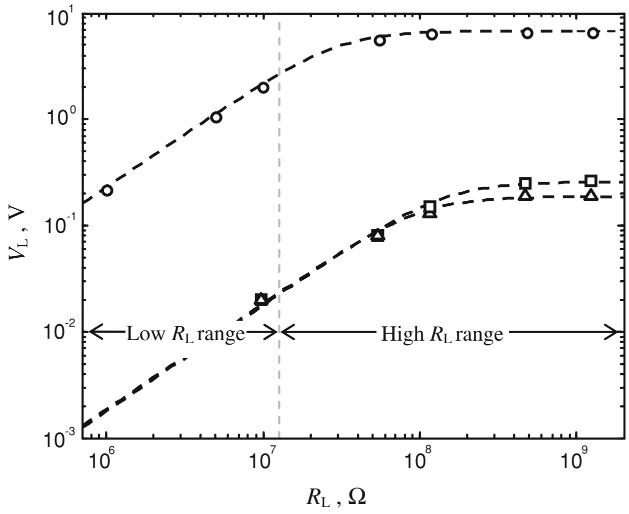

Fig. 4 Experimental measurements of amplifier's capacitances. Main-powered multichannel biopotential acquisition system (case 1 in Table 2) (*circles*), battery-powered isolated device (case 2 in Table 2) (*squares*), and small battery-powered wireless system (case 3 in Table 2) (*triangles*). The *curves* in *dashed line* correspond to Eq. 1 for the estimated C_{SUP}, C_{ISO} values

Table 2 Coupling capacitances C_{SUP} and C_{ISO} for different kinds of amplifiers

#	Amplifier description	C_{ISO} (pF)	C_{SUP} (pF)
1	Main-powered EEG multichannel acquisition system.	99.6	3.31
2	Battery-powered, connected to a PC through an isolated USB port (ADUM 4160 of Analog Devices).	29.2	0.03
3	Battery-powered, small wireless EEG system.	18.4	0.03

main-powered through a 50 Hz isolation transformer, C_{ISO} results of around 100 pF and C_P of few pF. For small battery-powered devices, these capacitances reduce to 30 pF and hundredths of pF respectively. It is important to note that for these extremely low capacitances values, C_{ISO} also depends on the site where the devices are placed on, because it is also linked to ground and power line by its own coupling capacitances.

4 Discussions

A method to estimate the EMI condition for biopotential amplifiers was proposed and experimentally evaluated for some typical conditions. The agreement observed between EMI model and experimental data is very good and the proposed method can be also useful for teaching purposes on biomedical instrumentation courses.

The patient-power line capacitance C_P is typically of tenths of pF, but it can increase up to 2–3 pF, when the patient touches main-powered devices. The patient-ground capacitance C_B verifies the usual adopted values of 100–200 pF; but in some cases, as touching large area surfaces, it can be as high as 4 nF. These extreme C_B values jeopardize the stability of the DRL circuit, which must be designed taking into account these cases [11, 12].

The common mode interference voltages V_{CM} can be of several tenths of mV for a main-powered amplifier, whereas it is below few mV for high-isolation systems. In this case, V_{CM} does not impose a serious problem, and a Common Mode Rejection Ratio (CMRR) of 60–70 dB is enough to keep power-line interference below the amplifier noise level.

The effects of power-line electric field interference in biopotential measurements can be accurately described by the usually accepted model of lumped coupling capacitances. The proposed method provides a simple and inexpensive way to estimate these capacitances for particular EMI conditions.

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