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Switch Configuration Effect on Stray Capacitance in Electrical Capacitance Volume Tomography Hardware

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Abstract

Electrical capacitance volume tomography (ECVT) system uses six switches in one channel with configuration resembling "T" letter, so it is called "T-switch". The working scheme of the switch can be explained in four different modes of operation, i.e. excitation mode, detection mode, ground mode, and floating mode. This research describes the effect of switch configuration to stray capacitance in ECVT hardware. Stray capacitance introduces parasitic signal from other sources; one of them is signal from another electrode at floating mode when the signal is still flowing to detection circuit. One channel, two channels, three channels, so on until thirty-two channels are connected to single detection circuit sequentially to investigate the effect of stray capacitance. Both simulation and experiment show the stray capacitance increases along with addition of channel corresponds to 0.046pF for each channel.

Keywords: *Stray capacitance, T-switch, ECVT, C-V circuit*

1. Introduction

Electrical capacitance volume tomography (ECVT) is one of 3D image visualization techniques based on permittivity distribution from capacitance measurement inside 3D sensor. Applications of ECVT are very wide from industrial to medical field such as multiphase flow, shale gas detection, breast and brain scanning, also being developed for non-radiation full-body scanning. Figure 1 shows a typical block diagram of ECVT system, which has three main part i.e. 3D sensor, data acquisition system, and personal computer. Various geometry of the sensors have been designed to adapt the ECVT for different application. There are cube, conical, twin-plane cylinder for high pressure and high temperature application [1]; hemisphere for breast scanning [2]; helmet for brain activity scanning [3]; bend, T-shape, half-cylinder for flow imaging [4]; and other geometry designs.

Figure 1. Block diagram of ECVT system

The problem in ECVT system is low resolution, hence image reconstruction is not good, ill-posed reconstruction problem, much more artefact, and the image attracted upwards and

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downwards at both ends of the sensor. Typically, ECVT sensor has large 32 electrodes plate (4x8) in four planes configuration with each plane has eight electrode as depicted in Figure 1. The configuration has high sensitivity and high signal-to-noise ratio, but less number of measurement data, hence reducing the image resolution. Small electrode could increase the resolution and number of measurement data, but reduce the sensitivity and signal-to-noise ratio. To overcome these challenges, sensor design using small electrode connected together to form a large electrode will increase the number of measurements data and image resolution without reducing the sensitivity and signal-to-noise ratio [5]. Another way to increase the accuracy is by improving the detection circuit e.g. using quadrature phase detection algorithm [6] and arranging the sensitivity distribution by controlling distance of electrode pairs [7]. Combining some electrodes together needs additional electronic switches, which can cause another problem such as increasing of stray capacitance.

The accuracy of capacitance measurement is influenced by some factors, one of them is stray capacitance. Stray capacitance is parasitic signal from other sources and affected by some factors such as screen enclosure, cable connecting sensor with data acquisition system, and switch used for selecting electrode pair [8]. Usage of axial and radial guard in the sensor design would reduce the fringe effect and stray capacitance, which occur from the rear of electrode pair [9]. Coaxial cable is one of sources of stray capacitance that is high enough, about 100 pF per meter length. Stray capacitance from coaxial cable can be damped by putting the capacitance-to-voltage circuit (C-V circuit) close to sensor. Another source of stray capacitance is switch for selecting electrode pair. This paper will discuss how the switch could affect stray capacitance. Each channel has at least six switches connected to the C-V circuit. Some researcher use a single C-V circuit for each channel to reduce stray capacitance, but the more the number of channel, the more complex the hardware, inefficient, and also introducing more noises too. Other researchers use a single C-V circuit for all channels, therefore the hardware is more simple, noise from operational amplifier can be reduce, but has another problem that is high stray capacitance derived from switch.

In this work, the effect of switch configuration to stray capacitance in ECVT hardware will be described. Working scheme of the switch can be explained in four different mode of operation, i.e. excitation mode, detection mode, ground mode, and floating mode. All will be described in section 2.1. From the switch modes, equivalent circuits are examined to get mathematic models, and then simulated using Matlab with parameters from datasheet in order to observe the effect of stray capacitance. We used data acquisition system that has 32-channel for experiment to prove simulation results. All channels connected together to a single C-V circuit, one channel, two channels, three channels, and so on until thirty-two channels connected to single C-V circuit sequentially to investigate the effect of stray capacitance.

2. Hardware Design Method

2.1. Switch Network Configuration

Basic principles of capacitance sensor is the difference in potential between two electrodes, afterward capacitance value among electrodes can be calculated by the charge density divided by voltage difference among the electrodes, and written as an equation [10]:

$$C_{ji} = \frac{Q_{ji}}{V_j - V_i} \tag{1}$$

Where C_{ji} is capacitance between electrode *i* and *j*, Q_{ji} is charge on electrode *j* induced by potential difference between V_j - V_i, V_i is potential on electrode *i*, V_j is potential on electrode *j*. The difference in potential between two electrodes can be obtained by activating pair of electrodes as excitation and detection. Based on principle of capacitance tomography, all electrodes should be scanned to get capacitance data, hence each electrode can act as excitation or detection. It is necessary for switch network to accommodate all electrodes, which is capable of connecting each electrode to a excitation source or detection circuit. Various switch configurations for each electrode modes are shown in Figure 2.

The switch configuration as shown at figure 2 formed as the letter *"T"*; hence, it is called *T-switch*, and some researcher used this notation [11-13]. With the configuration, each electrode can connect to excitation source or detection circuit depending on the given control signal. In this design we used Complementary Metal Oxide Semiconductor Integrated Circuit (CMOS IC) DG470 manufactured from Vishay Siliconix. The switch type in this chip is SPDT (single pole dual tap), which has one common connection pin and two connection pins i.e. NO (normally open) and NC (normally closed). Some specifications include supply voltage 44 volt, analog signal range ±15 volt, low on-resistance 3.6 ohm, off-capacitance of 85 pF, on-capacitance of 125 pF, capacitance-to-ground of 37 pF [14]. Specifications described above are considered in switch network design.

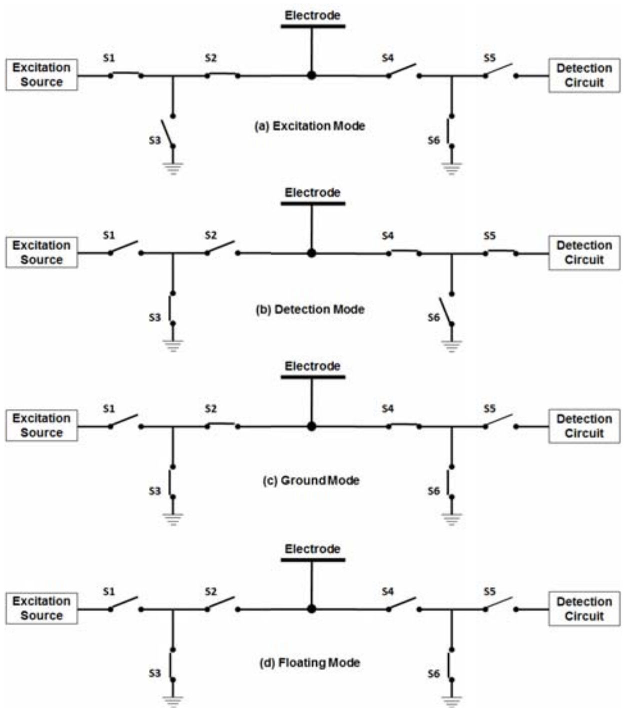

Figure 2. Switch network configuration for different mode

The working scheme of switch network can be explained in four different modes of operation, i.e. excitation mode, detection mode, ground mode, and floating mode. In excitation mode: switch S_1, S_2, and S_6 are closed whereas switch S_3, S_4, and S_5 are opened, hence the electrode is connected to excitation source, and the signal can be transmitted. In excitation mode, closed switch S_6 has function to prevent signal leakage from excitation source through switch S_4 flows to virtual earth. For detection mode: S_1, S_2, and S_6 are opened whereas switch S_3, S_4, and S_5 are closed, hence capacitance signal is being converted into voltage signal inside detection circuit. In detection circuit, closed switch S_3 has function to prevent the signal leakage from excitation source through switch S_1 flows to virtual earth. Ground mode: switch S_2, S_3, S_4, and S_6 are closed whereas switch S_1 and S_5 are opend, hence the electrode is connected to virtual earth. Floating mode: switch S_1, S_2, S_4, and S_5 are opened whereas switch S_3 and S_6 are closed, hence the electrode is open circuit.

All configurations should be implemented on all electrodes. A path along electrode to the excitation source needs three switches as well as to the detection circuit, therefore each electrode needs six CMOS switches. Accommodating 32-electrodes requires 192 CMOS switches, which could be functioned in any mode of configuration.

2.2. Detection Circuit

The capacitance signal from electrode pairs needs to be converted into voltage signal for further processing using an electronic circuitry namely capacitance-to-voltage (C-V) circuit. The C-V circuit is built by an operational amplifier, feedback resistor, and feedback capacitor which would convert the current into ac voltage [15, 16] as shown in Figure 3. Capacitance connected at the input and output of the electrode is stray capacitance (Cq) which is imposed by screen sensor, cable, and electronic switches [6]. Base on the Kirchhoff law, current entering node and leaving node is equal (i_1=i_2), thus, the voltage representing capacitance measurement can be retrieved from:

$$V_o = \frac{kV_iC_x}{C_f};\ k = \frac{R_f}{R_f + {}^1/_{j\omega C_f}} \tag{2}$$

In the equation, V_o is voltage output that represents capacitance measurement, V_i is sinusoidal voltage input injected to the electrode, R_f is feedback resistor, C_f is feedback capacitor, ω is angular frequency, C_x is object capacitance to be measured. This equation contains two elements i.e. capacitive and resistive. Smaller resistance value causes greater conductivity and vice versa. In the capacitance measurement method, conductivity will be damped by setting $k \cong 1$, which can be made by selecting suitable value of R_f and C_f.

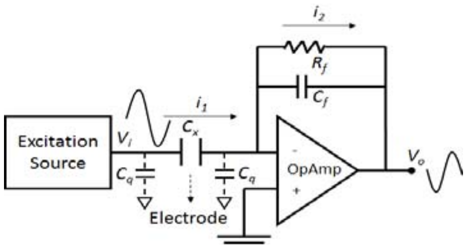

Figure 3. Capacitance-to-voltage circuit (C-V circuit)

Capacitance being measured on C-V circuit above is actually C_x and C_q, whose stray capacitance measured in parallel with C_x, hence total capacitance namely standing capacitance (C_s) [16]. In the capacitance measurement, stray capacitance is the parasitic capacitance that always present in every measurement, which is caused by coaxial cable along sensor and data acquisition system, CMOS switch to arrange each electrode as excitation and detection, and screen sensor surrounding electrode. Stray capacitance can reduce the measurement sensitivity in the electronic circuit.

2.3. Equivalent Circuit of Switch Network

Choice of the CMOS switch is limited by the need to cover excitation source signal level used in system, typically is below 15 Vp-p. The chosen CMOS switch is DG470 with specification as described in section 2.1. There is one switch in one IC package, so there is no capacitive crosstalk between switches, but there is capacitance to ground around 37 pF on each switch terminal. Figure 4 represents equivalent circuit of switch network for one electrode channel, which has two parts i.e. equivalent switch for excitation source on the left side and equivalent switch for detection circuit on the right side. Each CMOS switches has series component C_s, R_s also has capacitance to ground (C_g).

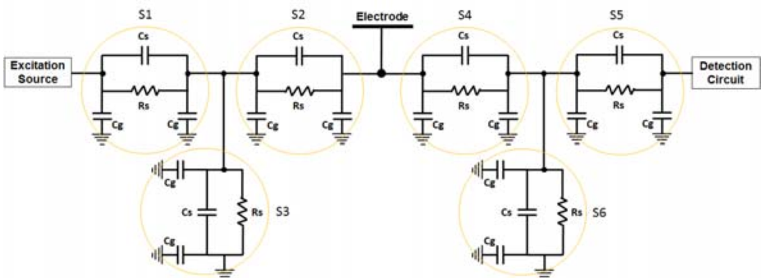

Figure 4. Equivalent circuit of switch network for one electrode

In ECVT hardware, each channel has excitation signal independently with adequate high voltage, hence the excitation circuit is stray-immune. The part that suffers the most impact by stray capacitance in ECVT hardware is the detection circuit, therefore analysis in this work focused on detection circuit. In detection mode, switch S_4, S_5 "on" while switch S_6 "off", one of terminal on S_6 connected to ground, hence the point between S_4, S_5, S_6 connected as parallel with three C_g and C_{soff} as depicted in Figure 5.

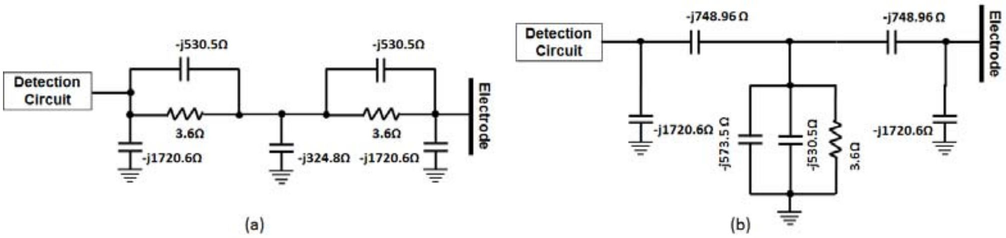

Figure 5. Equivalent circuit with imaginary value; (a) detection mode; (b) floating mode

Floating mode is also influenced by stray capacitance in detection circuit. Switch S_4, S_5 "off" while switch S_6 "on", therefore the point between S_4, S_5, S_6 connected as parallel with three C_g, C_{son}, and R_{son}.

3. Stray Capacitance on Switch Network

Initial capacitance will present in the ECVT hardware prior to measurement process, it is called stray capacitance, which marked by voltage occurence at the C-V circuit output. To analyze the effect of switch to stray capacitance, circuit above needs to be converted in impedance circuit form, with all components in complex values as shown in Figure 6. Impedance on Z_1 and Z_5 represent capacitance C_g; impedance on Z_2 and Z_4 represent switches S_5 and S_4 that has value $R_{son}//C_{son}$ for detection mode and C_{soff} for floating mode; impedance on Z_3 represents switch S_6 that has value $3C_gC_{soff}$ for detection mode and $3C_gC_{son}//R_{son}$ for floating mode.

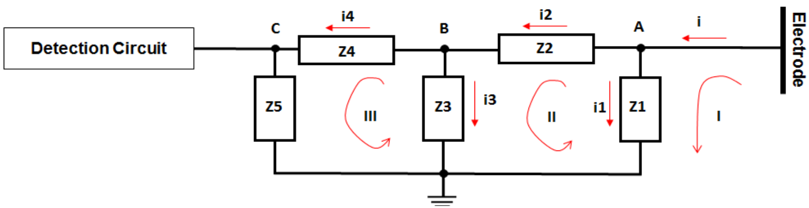

Figure 6. Simplification of the circuit for analyzing the switch effect to stray capacitance

The impedance on each component can be calculated using equation as follows:

$$Z_1 = Z_5 = \frac{-j}{\omega C_g} \quad (3)$$

$$Z_{2de} = Z_{4de} = \frac{Z_{Ron}Z_{Cson}}{Z_{Ron}+Z_{Cson}};\ Z_{Cson} = \frac{-j}{\omega C_{son}} \quad (4)$$

$$Z_{2fl} = Z_{4fl} = \frac{-j}{\omega C_{soff}} \quad (5)$$

$$Z_{3de} = \frac{-j}{\omega(3C_g+C_{soff})} \quad (6)$$

$$Z_{3fl} = \frac{Z_{ct}Z_{Rson}}{Z_{ct}+Z_{Rson}};\ Z_{ct} = \frac{-j}{\omega(3C_g+C_{son})} \quad (7)$$

Where $Z_{2de}, Z_{4de}, Z_{3de}$ is impedance on detection mode while $Z_{2fl}, Z_{4fl}, Z_{3fl}$ is impedance on floating mode. Moreover, we can find the current and voltage equation on each the branching points as follows:

$$i = i_1 + i_2 \quad (8)$$

$$i_2 = i_3 + i_4 \quad (9)$$

$$V_A = i_1 Z_1 \quad (10)$$

$$V_A = i_2 Z_2 + i_3 Z_3 \quad (11)$$

$$i_3 Z_3 = i_4 Z_4 + i_4 Z_5 \quad (12)$$

The voltage drop to detection electrode is very small about 10 – 20 mV, hence $V_A = 0.02\cos 2\pi f\ (V)$ 2.5MHz was used in simulation to analyze stray capacitance on switch network. By using (8) until (12), current on each branching points can be calculated and the results are shown on Table 1. The values in the Table 1 are in imaginary and phasor forms in order to facilitate further calculation. In the detection mode, current from electrode *(i_1)* is about 84.8 μA then splitted into i_1, i_2, and i_3. Consequently, current flowing to i_4 decreases to 11.6 μA. For the floating mode, current from electrode *(i_1)* is about 38.3 μA then splitted into to i_1, i_2, and i_3. Consequently, current flowing to i_4 decreases to 38.9 nA. In ideal condition when floating mode, current i, i_1, i_2, i_3, i_4 should not flowed into detection circuit, however in fact the currents are still flowing into detection circuit through C_{soff} in switches S_5 and S_4, hence it causes stray capacitance.

Table 1. The current values on each branching points

	Detection Mode	Floating Mode
i	$9.88x10^{-7} + j8.48x10^{-5}$ or $8.48x10^{-5}\cos(2\pi f + 1.56^o)$	$1.28x10^{-7} + j3.83x10^{-5}$ or $3.83x10^{-5}\cos(2\pi f + 1.57^o)$
i_1	$j1.16x10^{-5}$ or $1.16x10^{-5}\cos(2\pi f + 1.57^o)$	$j1.16x10^{-5}$ or $1.16x10^{-5}\cos(2\pi f + 1.57^o)$
i_2	$9.88x10^{-7} + j7.32x10^{-5}$ or $7.32x10^{-5}\cos(2\pi f + 1.56^o)$	$1.28x10^{-7} + j2.67x10^{-5}$ or $2.67x10^{-5}\cos(2\pi f + 1.57^o)$
i_3	$8.11x10^{-7} + j6.16x10^{-5}$ or $6.16x10^{-5}\cos(2\pi f + 1.56^o)$	$1.67x10^{-7} + j2.67x10^{-5}$ or $2.67x10^{-5}\cos(2\pi f + 1.56^o)$
i_4	$1.77x10^{-7} + j1.16x10^{-5}$ or $1.16x10^{-5}\cos(2\pi f + 1.56^o)$	$-3.89x10^{-8} + j7.52x10^{-10}$ or $3.89x10^{-8}\cos(2\pi f + 3.12^o)$

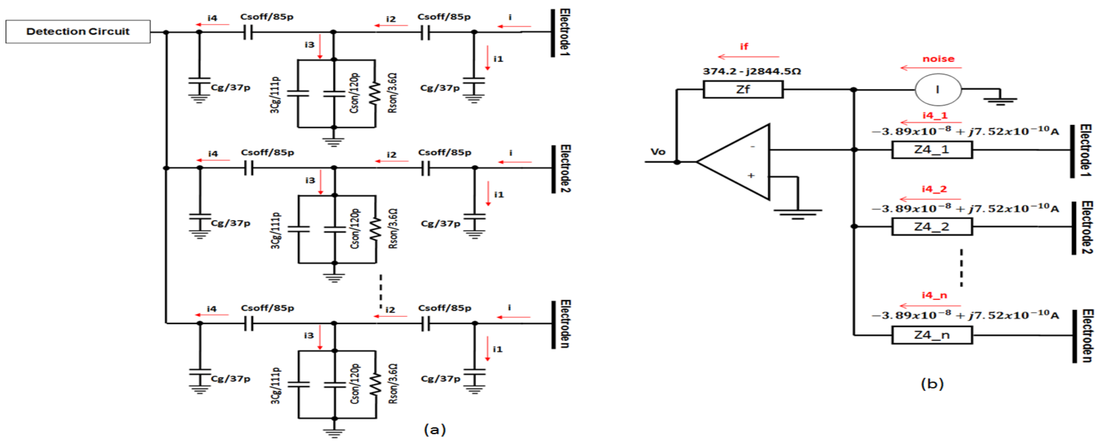

Figure 7. Each channel connected together through electronic switches causes stray capacitance; (a) equivalent circuit; (b) Simplification of each channel

The current i_4 based on Table 1 is very small about 38.9 nA for one channel, if some channels are connected together through switches, the current flowing into detection circuit will increases as depicted on Figure 7, hence increases stray capacitance. Figure 7(a) shows equivalent circuit; whereas Figure 7(b) shows simplification of each channel. The aim of merging channels is to connect small electrode to form larger electrode through electronic switches as described in section 1.

4. Results and Analysis

This circumstance makes current influence to stray capacitance is i_4 about $-3.89x10^{-8} + j7.52x10^{-10}$. In this case, switch network circuit connected to detection circuit will be analyzed. The switch network connected to charge amplifier or C-V circuit has function to convert current into voltage. Impedance Z_f represents resistor and capacitor ($R_f//C_f$) having values of 22KΩ and 22pF respectively, with voltage excitation of 20Vp-p, impedance Z_f can be obtained at $374.2 - j2844.5\Omega$. Circuit configuration on Figure 8 is the summing amplifier circuit, so that current flowing through branching points will increase the I_f current. Consequently, voltage signal at the output of Op-Amp increases, hence stray capacitance is much larger.

Stray capacitance is calculated using (2), all parameters are then simulated using Matlab in two conditions. First, ideal condition where only parameters based on datasheet are used in simulation. Second, adding random current noise about 19 – 22 μA in simulation. Experiment on ECVT hardware needs to be done to prove the simulation results. Experimental data is gathered using data acquisition system DAQ33201 sufficient for 32-channel acquisition of data. All channels connected together to a single C-V circuit, with one channel, two channels, three channels; so on until thirty-two channels connected to single C-V circuit sequentially to investigate the effect of stray capacitance. Subsequently, voltage signal at Op-Amp output is recorded and analyzed, and the result shown on Figure 9. Total current i_4 and voltage signal at Op-Amp output can be calculated with the following equation:

$$i = i_1 + i_2 + \cdots + i_n + i_{noise} \quad (13)$$

$$V_o = -iZ_f \quad (14)$$

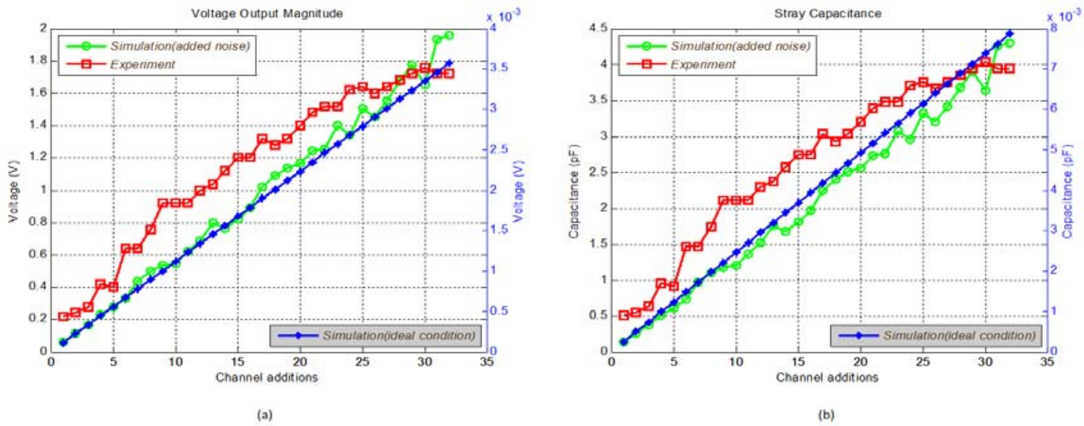

Figure 9. The effect of additional channel towards: (a) Voltage output magnitude; (b) Stray capacitance

Based on graphics on Figure 9, the simulation in ideal condition resulting in low value down to Pico Farad instead of Femto Farad $(1fF = 10^{-3}pF)$, this is due to no noise added in simulation and only parameters in the datasheets used in simulation (blue line). In fact, the circuit in ECVT hardware has noise from other sources such as PCB design, components layout, excitation signal that passes through PCB track, and adjacent track in parallel, which can cause capacitance effect. The CMOS switches also generate electromagnetic interference (EMI) [17], and some grounding in the circuit also conduct EMI [18]. Hence, the simulation with additional noise as mentioned before gives results in value of Pico Farad (green line); and so does the experiment results in order of Pico Farad (red line).

5. Conclusion

The switch network in ECVT is very important as the signal entrance from electrode, where it has four mode of operations i.e. excitation mode, detection mode, ground mode, and floating mode. Switch used in ECVT hardware is DG470 that has specific parameters including low on-resistance and low on-capacitance. Adding of switches necessary to connect some electrodes together will increase stray capacitance which is indicated by increasing of voltage at Op-Amp output. Both of simulation and experimental data show that channel addition will increase the stray capacitance as large as 0,02V and 0,046pF. Stray capacitance strongly influences measurement accuracy, sensitivity, and resolution. Therefore, it is very important to notice in PCB design and components layout, that excitation signal should not pass through PCB switches. Moreover, two parallel tracks in PCB design which can cause capacitance effect also need to be considered.

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