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Investigation of error in simulation of analogue part of voltage measurement system in Proteus

Iliya E Petrov

Department of Electronics, Faculty of Electronics and Automation, Technical University of Sofia, branch Plovdiv, Plovdiv, Bulgaria

E-mail: iedu@abv.bg

Abstract. The further development of simulator programs for electronic and electric circuits gives opportunities for very close to real laboratory experimental work. New problems are emerged with models of parts that previously were not being object of simulation. The paper is provoked from problem in simulation of voltage measurement system that measure voltages in 4 ranges in ISIS Proteus software package. The first attempt of modelling the measuring system gave very disappointing simulation results: the error from measurement was more than 4 percent. The necessity to investigate the sources of this error to reduce it in acceptable limits is aroused. The paper gives recommendations for designers, researchers, scientists and every user of similar simulator software to take into account parameters of such simple elements of the circuits as switches. The choice of the Op Amp in input amplifier is also very important when a minimum error in simulation of measurement system is needed. The focus on investigations is analogue part of the electronic system but the whole circuit with A/D Converter, microprocessor part and indication is described. The aim is to show advantages that ISIS Proteus simulation package suggest for modelling of complex electronic devices.

1. Introduction

The need of simulation of electronic circuits starts long before PC development. In nowadays the PCs, laptops and smart phones are elsewhere and the access to the simulation software is very easy. Softwares that exist are as free as shareware. Some simulators reached such high level that they not only simulate mathematically physical processes in the electronic devices but also strive to create sensing of real device and laboratory environment. For example, LED lights, motor spins, LCD display shows text or graphic information etc. There are models of voltage and current meters, oscilloscopes that measure in real time and display the desired magnitude. One of these simulators of electric and electronic circuits is ISIS Professional from package Proteus. This simulator is very user-friendly but it is not as famous as OrCAD PSpice – there are not so many publications about Proteus and they are principally focused on its educational aspects [1], [2] ([3] discusses also research possibilities of Proteus).

The simulation in ISIS is interactive – the user could rotate switches, push buttons, move potentiometers and simultaneously view the change of the results of the simulation. The simulation of microprocessor circuits with their Assembler code and many displaying units is also a great advantage of this simulator. These features are used in modeling of the investigated voltage measuring system.

Involving models of such simple elements as switches in software like ISIS Proteus places new problems for solving especially when the simulation of precise measuring devices is accomplished. The system investigated in this paper runs into such problem so it needs clarifying.

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2. Description of the circuit

The modelled and simulated in ISIS Proteus circuit is shown on figure 1. A brief description of the main parts of the scheme will be made. The input voltage that is measured is connected through 4-positions rotating switch SW2 to input voltage divider. The ranges are 200V, 20V, 2V and 200mV. The dividing coefficients are 1000, 100, 10 and in the smallest range the measured voltage is connected directly to the input amplifier. So the input voltages to the amplifier are between 0V and 200mV. To reach the range of the A/D converter, that is 5.12V, the amplifier must multiply the input range 5.12/0.2=25.6 times. The input amplifier is built on standard circuit of non-inverting amplifier. The formula for the gain of this circuit is well known:

$$K = 1 + \frac{R7}{R9} = 25.6 \qquad (1)$$

By the chosen value of resistor R9=11kOhm, for the value of R7 is obtained R7=24.6*11k=270.6kOhm. The resistor R1 is for compensation of the input currents of Op Amp and the value is R7||R9. The impact of this source of errors in Op Amp circuits is given in [4].

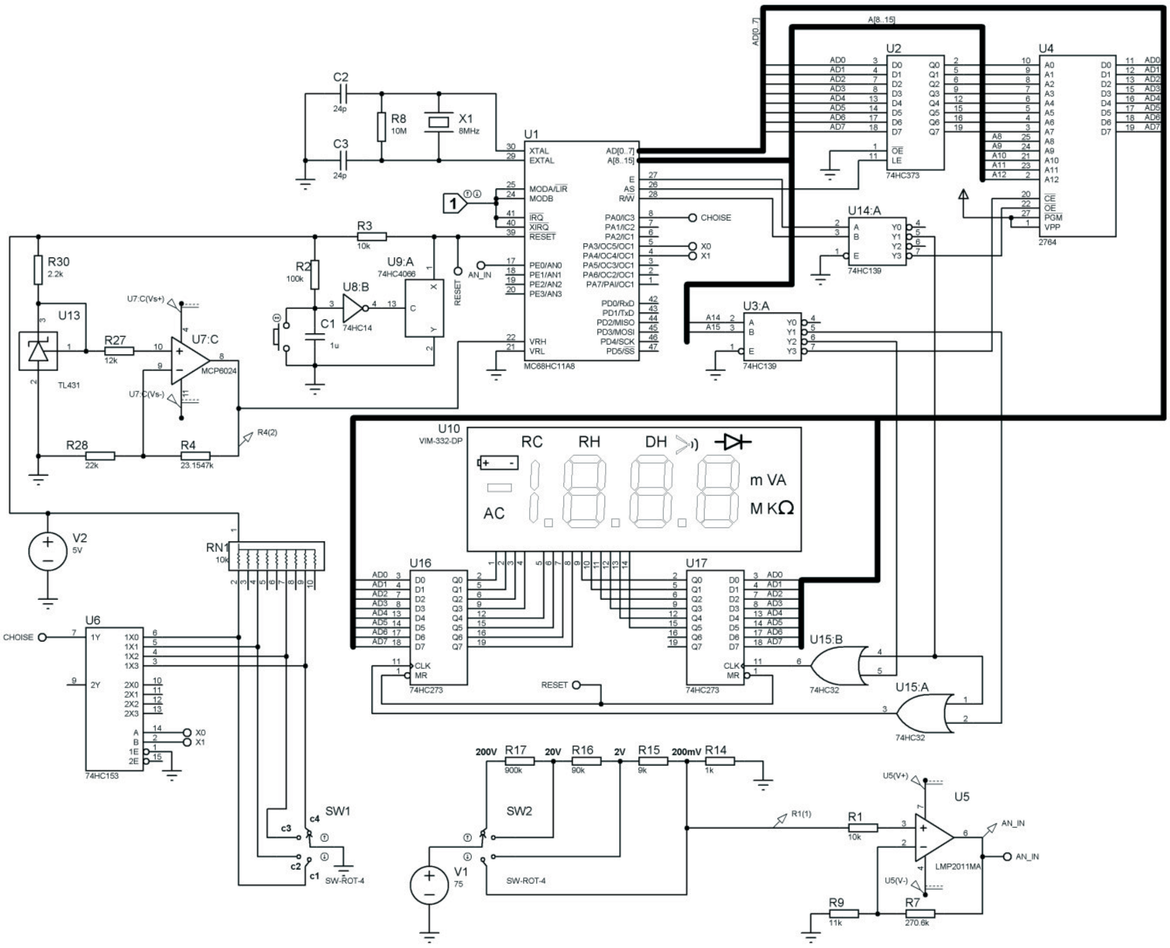

Figure 1. Modelled and simulated in ISIS Proteus voltage measurement system.

Another analogue circuit in figure 1 is for reference voltage for A/D Converter. It is received from IC TL431 and buffer amplifier consisted of Op Amp MCP6024 and defining the amplification resistors R4 and R28. The gain is determined by similar to the equation (1). The exact voltage of 5.12V is tuned experimentally by changing the value of R4.

The digital and microprocessor part of the scheme includes microcontroller 68HC11. It has integrated software and hardware support in ISIS Proteus. The standard parts belonging to microcontroller are circuit for providing clock pulses (X1, C2, C3, R8 and internal circuitry), reset circuit, demultiplexer of LS Byte of AD Bus (register 74HC373), program memory 2764, circuit for obtaining write command (74HC139) and address decoder 74HC139 for chip select of registers 74HC273, that control the 3 ½ digit display. The choice of extended mode of µC 68HC11 is set by virtual unit LogicState with logical 1.

The last unit in digital part of the voltage measurement system embeds the digital multiplexer 74HC153. It is used one half of the IC for defining the state of the switches and which of the ranges is chosen. The multiplexer is controlled by microcontroller 68HC11 by outputs X0 and X1, and his state is sampled by input CHOISE.

3. Results from the first run of the simulation

The first results from a simulation of the described system by the conditions: measured voltage: 75V, range: 200V, Op Amp in input amplifier MCP6024, 8-bit ADC, embedded in µC 68HC11 showed the following: indicated voltage on 3 ½ display: 78.1V.

Therefore the absolute error in this measurement was 78,1-75=3.1V, corresponding to relative error δ=3.1/75*100=4.13%. The error relevant to LSB is 3.1/1000*25.6/0.02=4 rounded. And this is in 8-bit A/D Converter case. Obviously this simulation was failed.

Several questions were raised: What is the origin and which are the sources of such huge error. The first attempt to reduce the error was changing the Op Amp. From the Libraries of ISIS Proteus were found only High Precision models of Op Amps as LMP2011, LMP2016, LMV2011, MAX4236, MAX4237, OP97, OPA227, OPA228 etc. The change of Op Amp gave variable success. The supply voltages of Op Amp become another source of error in the simulation.

Finally, the greatest source of errors was found in switches, especially, SW2. The default value of the off resistance is relatively small 100MOhm. Changing this value to 10GOhm, significantly minimized the error of the voltage measurement.

4. Investigation of the sources of error

4.1. Analysis of the influence of Roff and Ron resistance of the switch

The in-depth analysis of the error due to parameters of the switches showed the configuration of the Ron and Roff resistances. They are only between input terminal and all bubble terminals but not between bubble terminals. The verification of the model was carried out in OrCAD PSpice (figure 2).

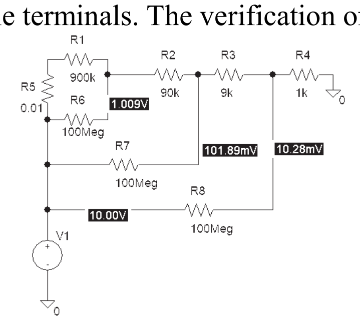

Figure 2. Modelling of input voltage divider with switch in OrCAD PSpice. The state of the switch is turn on to range 200V.

A script in MATLAB is written to extend the range of the values of these resistances and to obtain the results in graphic form. Some statements of MATLAB code will be commented. Roff resistances are formed as a vector in logarithmic space `Roff=logspace(8,10,1001)` between 10^8 and 10^{10} Ohm, 1001 elements. Values of the resistors in resistor divider are the same as in the scheme, shown on figure 2. When the range is selected by the switch to 200V, the equivalent resistance according to voltage source is calculated by the following program code:

```
Req1=par(par(par(Ron+R1,Roff)+R2,Roff)+R3,Roff)+R4;
```

The function `par()` is used for calculation of the equivalent resistance of 2 resistors in parallel.

The output of the divider in mV is calculated next:

```
Uout1rng=Ux*R4./Req1*1000;
```

The relative error for the range 200V is

```
RelErr1=(Uout1rng-Ux)/Ux*100;
```

Analogous program code is written for ranges 20V and 2V. The graphical results of the investigation of the influence of Roff resistance over input voltage divider are given on figure 3.

The results show that the Roff resistance of 100MOhm by 200V range gives the maximum relative error from 2.75%. This value is constant for all input voltages in the range. The explanation is that the circuit is linear. The error is decreasing exponentially when Roff is increasing.

Further research shows that the Ron resistance impacts significantly in the smallest range by high values of Roff resistance. Graphical results of this investigation are given on figure 4. Roff resistance is 10GOhm.

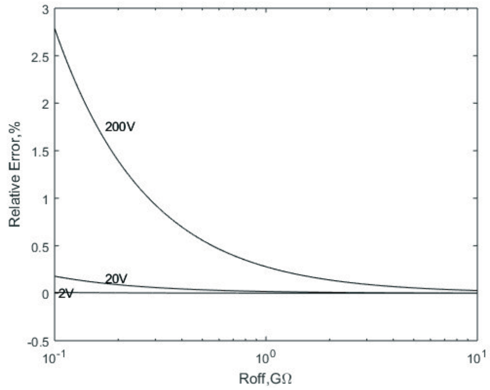

Figure 3. Influence of Roff resistance of the switch on the error. Ron is 10mOhms.

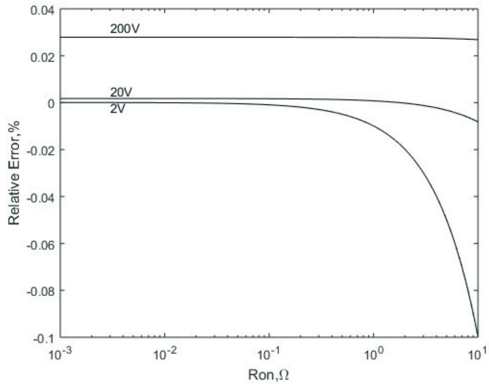

Figure 4. Influence of Ron resistance of the switch on the error.

It is seen that the error is 100 times smaller than this one shown on figure 3. The maximal error 0.1%, not regarding the sign, is obtained in the range 2V and 10Ohm Ron.

4.2. Improved modelling in ISIS Proteus

The simulation results in ISIS Proteus after the analysis of the influence of Roff and Ron resistances of the switch and changing the operational amplifier as follows: Op Amp in input amplifier LMP2011, Roff of the switch SW2 to 10GOhm and Ron resistance 10mOhm showed on the display, the exact value of the measured voltage 75.0V.

At first glance the error is 0, but the results in analogue part of the system show absolute error on the input of the amplifier 20.7μV, that corresponds to the output to 0,55mV absolute error. The last value is almost 40 times smaller than LSB. So with the improvements in the analogue part of voltage measurement system, the A/D converter could be 5 or 6 bits greater, reaching 13 or 14 bit precision.

Table 1 shows results of the simulations of the analogue part by experimenting with different precision Op Amps. The values of Roff and Ron resistances are not changed (Roff=10GOhm, Ron=10mOhm). Input voltage is 100mV, and the range is 200mV. As could be seen from figure 1, in this range there is no error (or it might be neglected) due to switch SW2, so the results from this investigation emphasise on error due to Op Amp only. The aim is to find best models of Op Amp according to precise measurement results.

It can be seen that the model OPA227 gives absolute error only 10μV, the next good result is with LMP2015 where the absolute error is 30μV. The worst from the experimented models of Op Amp is OA_JFET where the absolute error reaches value of 128.73mV (12873 times more than OPA227). The results from table 1 show that the precision choice of Op Amp is needed to improve error in simulation of voltage measurement system.

Table 1. Output voltages of the analogue part of voltage measurement system by different Op Amp in 200mV range and 100mV input voltage.

Op Amp (Model)	Main features	U_{amp}, V
OPA4227PA (OPA227)	Supply range ±2.5V to ±18V A_{VOL}=160dB (Typ) Offset voltage 75μV Input Bias Current 10nA	2.56001
LMP2015MA (LMP2015)	High Precision A_{VOL}=130dB Rail-to-Rail output 30mV	2.55997
4559 (OA_BIP)	Offset voltage 75μV Input Bias Current 2.5nA	2.58599
ADTL082ARZ (ADTL082)	Low Cost JFET Input Op Amp	2.59281
TL082 (OA_JFET)	General purpose Op Amp	2.43127

Table 2 presents extended results of the simulation in ISIS Proteus where Op Amp is fixed to LMP2011MA. From the value in column Amplifier, U_{amp} from row 3 from the bottom – 2,55998 V, this model of Op Amp could be classified between OPA227 and LMP2015, with absolute error 20μV.

Table 2. Simulation Results by LMP2011MA Op Amp, Roff=10GOhm and Ron=0.01Ohm

Range	U_X, V	Input Voltage Divider			Amplifier				8-bit A/D Converter and Indication	
		U_{att}, mV	U_{id},mV	δ, %	U_{amp}, V	U_{id2}, V	δ_2, %	Error in LSB	value of ADC	Indication
200V	200	200.056	200	0.0280	5.12136	5.12	0.0266	0.0680	FF	199.2
	100	100.028	100	0.0280	2.56071	2.56	0.0277	0.0355	80	100.0
	50	50.0138	50	0.0276	1.28037	1.28	0.0289	0.0185	40	50.0
	20	20.0054	20	0.0270	0.512171	0.512	0.0334	0.0086	1A	20.3
20V	20	200.003	200	0.0015	5.12003	5.12	5.86e-4	0.0015	FF	19.92
	10	100.002	100	0.002	2.56005	2.56	0.0020	0.0025	80	10.00
	5	50.0007	50	0.0014	1.28004	1.28	0.0031	0.0020	40	5.00
	2	20.0002	20	0.0010	0.512037	0.512	0.0072	0.0018	1A	2.03
2V	2	200	200	0	5.11994	5.12	-0.0012	-0.0030	FF	1.992
	1	99.9998	100	-2e-4	2.56	2.56	0	0	7F	.992
	0.5	49.9998	50	-4e-4	1.28002	1.28	0.0016	0.001	40	.500
	0.2	19.9999	20	-5e-4	0.512028	0.512	0.0055	0.0014	1A	.203
200mV	0.2	199.998	200	-0.001	5.11989	5.12	-0.0021	-0.0055	FF	199.2
	0.1	99.999	100	-0.001	2.55998	2.56	-7.8e-4	-0.001	7F	99.2
	0.05	49.9995	50	-0.001	1.28001	1.28	7.8e-4	5e-4	40	50.0
	0.02	19.9998	20	-0.001	0.512007	0.512	0.0051	0.0013	1A	20.3

Some of the columns of Table 2 are explained:

1. U_X is the measured voltage. There are used standard specific values covering the range;
2. U_{att} is the voltage U_X after input voltage divider (the voltage across resistor R4 on figure 2);
3. U_{id} is the ideal value of U_{att} if the switch is ideal (Roff=∞ and Ron=0Ohm), the values of the resistor in voltage divider are exact and the input current of Op Amp is 0A;
4. The relative error δ is calculated by formula:

$$\delta = \frac{U_{att} - U_{id}}{U_{id}} * 100, \% \quad (2)$$

5. U_{amp} is the output voltage of amplifier. This is real measured output voltage, so it consist error from the voltage divider and errors due to Op Amp;
6. U_{id2} is the ideal output voltage of the amplifier if its input voltage is U_{id} and Op Amp is ideal;
7. Relative error δ is calculated analogically by equation (2), using the values of U_{amp} and U_{id2};
8. Error in LSB is the difference between U_{amp} and U_{id2} divided by LSB (5.12/256=20mV);
9. Value of A/D Converter is 8-bit result (hexadecimal number) of conversion of U_{amp};
10. Indication is displayed value of the measured voltage on 3 ½ digit display.

The simulation results presented in Table 2 confirm highest precision results in all ranges and in several important points in every range. It is seen that the error decreases if the range is smaller. In a fixed range the smallest voltages are with maximal error. This is due to non-idealities of Op Amp. In the smallest range the Ron resistance has great influence on the error along with parameters of Op Amp.

The experimenting with different models of Op Amp, showed that some of the models of Op Amps are very sensitive according to power supply voltages. For example, there were Op Amps LMP2011MA, LPM2015MA and LMP2016MA.

The latest discussion on the results is that the used A/D Converter is very low precision but the objective of the paper is focused on analogue part of the voltage measurement system rather than on mixed and microprocessor part. The greatest error in the beginning of the investigations was found exactly in the analogue part. Now when the sources of the errors in this part are identified and they are significantly reduced, the change of A/D Converter could be accomplished.

5. Conclusions

The significant improvement in precision in modelling and simulation of voltage measurement system is achieved due to analysis of the sources of errors in analogue part. It was proven that the most important source of the errors is Roff resistance of the switch in input voltage divider. The Op Amp is the next source of error. Using of only "High Precision" Op Amps with relevant power supply voltages increases punctuality. The Ron resistance has relatively small impact on error.

The main discussion was the error in analogue part but in simulation of the Assembler Code for µC 68HC11 was found error in instruction DAA-decimal adjustment is made with 9 of the result instead of greater than 9. This compelled to use another method, without using DAA instruction, for transform decimal numbers to hexadecimal and vice versa. The method is given in [5].

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