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A NEW MODEL FOR SIX TERMINAL HALL ELEMENT

Aleksander Sešek, Janez Trontelj

Faculty of Electrical Engineering, Ljubljana, Slovenia

Key words: six terminal Hall element model, integrated coil, coil heating modeling, offset voltage modeling

Abstract: A new model for integrated six terminal Hall element is presented in the paper. The model is based on six terminal Hall element patented in 1995. All magnetic field contributions are considered, external magnetic field and inducted field with integrated coil. A new model was developed to improve the offset modeling and to understand the influence of the integrated coil heating on the Hall element output signal.

Nov model Hallovega elementa s šestimi priključki

Kjučne besede: Hallov element s šestimi priključki, integrirana tuljavica, vpliv segrevanja integrirane tuljavice, vpliv napetosti ničenja

Izvleček: V članku je predstavljen nov model Hallovega elemeta s šestimi priključki. Temelji na Hallovem elementu s šestimi priključki, ki je bil patentiran leta 1995. V model so vključeni vsi prispevki magnetnih polj, ki vplivajo na odziv elementa. To sta zunanje magnetno polje in notranje magnetno polje, generirano z integrirano tuljavico. Nov model optimizira simulacije vpliva ničelne napetosti in vpliva segrevanja integrirane tuljavice na izhodni signal Hallovega elementa.

1 Introduction

Back in 1995 six terminal Hall element was patented /1/. In the same time simple Hall model with coil was introduced. Basic model consists of fundamental elements. Four resistors were introduced in the model as replacement for n-well silicon resistance. As seen from the Figure 1, each resistor corresponds to one of branches in the layout picture, using the clover leave shape of the Hall element.

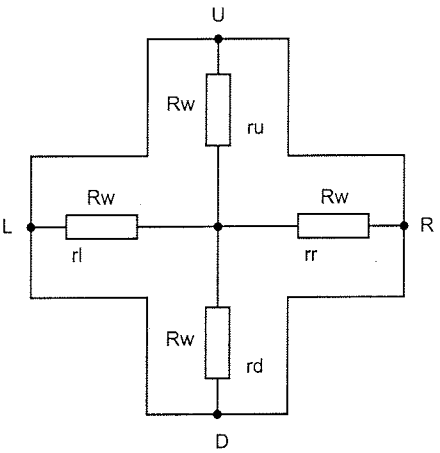

Fig. 1: Basic elements in Hall model

The contact terminals of Hall element are labeled as their orientation; U - Up, R - Right, D - Down and L as Left.

Next parameter which is implemented in basic model and the most important one is the Hall voltage. For the Hall voltage calculation the bias current needs to be measured which is flowing trough the element. Because we can spin the Hall element, the current must be measured in both possible directions, U - D and R - L. Then the current controlled voltage source is used to simulate Hall voltage on the opposite terminals. Finally the contribution to consider is the magnetic field, generated by the integrated coil. The solution is presented in Figure 2, which also presents the basic model for Hall element, introduced in 1995.

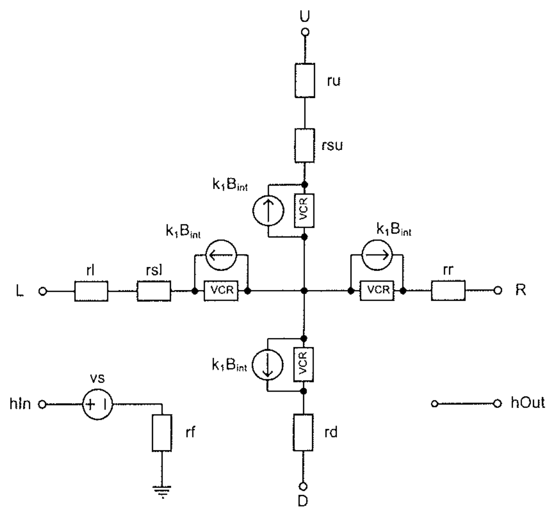

Fig. 2: Basic model of six terminal Hall element

In this figure we can see four basic well resistors ru, rr, rd and rl. Resistors rsl and rsu are the resistors for bias current sensing. Voltage drop on those resistors in mV is directly current value in mA if resistance is set to 1Ω. In each branch there is one closed loop which consists of VCR element (Voltage Controlled Resistor) and CCCS element (Current Controlled Current Source). VCR's are gu, gr, gd and gl elements in SPICE model and are controlled by the voltage on the current sensing resistor corresponding to which branch they are positioned. In the model the integrated coil resistance is replaced by resistor rf. Current trough the coil is in linear relation with magnetic field. With DC voltage source vs, this current is measured and it controls all CCCS elements. The pair of VCR and CCCS needs to be positioned in each branch because VCR element returns 0 for negative voltage, as the Hall element can be spinned this voltage can be negative as well, so the second pair of VCR and CCCS takes over for Hall voltage calculation.

Sensitivity of Hall element /3/ and resistance of n-well silicon varies with technologies. We can adjust the variations for each technology by changing of the coefficients in VCR and CCCS relations and with changing the values of well resistors.

At the simulations where offset influence is investigated, an external resistor between two terminals is used, i.e. if the current flows from U - D an external resistor between U and L or U and R is connected. The offset voltage is mainly caused with the process, nonidealities due to the tolerances in dimensions, etching, etc. Using the method of changing resistance between terminals, the offset voltage appears at the output, but from this approach we can not see clearly how big the actual variation of well resistance is. Second difficulty in simulations with external offset resistor is long settling time. Resistors values in the range 100 times larger then the resistance of the Hall element branch need to be used, to achieve correct offset levels. The settling constant is far too long, to simulate the spinning of the Hall element, where frequencies around 500kHz are used.

In the simple model, there is no external magnetic field influence element. Simulations with basic Hall model are done only with the internal coil. We need to add the external field and the internal generated field on the same terminal to observe the influence on the output. This approach does not give as clear separate contributions of each part of the magnetic field.

Influence of the coil heating is also not included in the basic model. Current flowing trough the coil causes coil heating which directly affect the Hall element output voltage.

2 New Hall model

In this section all problems mentioned above are solved by proposing one compact model of the Hall element. All parameters are characterized to reach the output response as close as possible to match the real measurement results.

Distribution of resistances in the basic model, are done as in the layout topology, in four separate branches. For the offset voltage simulation, this is not appropriate. A better solution is the bridge connection of four resistors, as shown in Figure 3.

In this case the offset voltage can be easily modeled by resistor value variations, according to the parameters derived from silicon foundry matching data. Relation between resistance variations and output offset voltage is linear and clear. Small change in resistance can cause a large output offset voltage, but it does not influence the settling constant. The resistances in the branches are now different than in the previous model. Total Hall element resistance is the same and output signal as well. In the Table 1, the offset voltage Voff simulation results are listed, were Δrur is resistance step value.

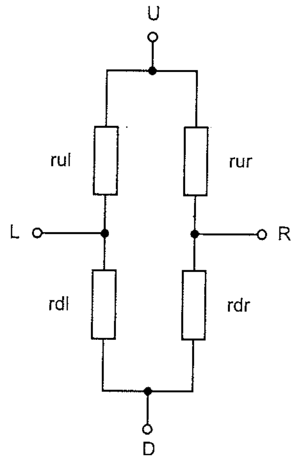

Fig. 3: Resistors bridge connection

Table 1: Offset simulation results

ΔRur[Ω]	Voff[mV]
0	0
1	-0,259
2	-0,517
5	-1,292
10	-2,582
20	-5,159
50	-12,859
-1	0,257
-2	0,516
-5	1,292
-10	2,587
-20	5,180
-50	12,990

On Figure 4 graphical result of the offset voltage is shown.

On the figure 5a the modeling of Hall voltage is added to the bridge model of Hall element. Two separate voltage sources are included for external and internal field contributions in each of bridge branches. Each voltage source consists of VCR and CCCS as in the basic model. For current sensing, two resistors are added in the common Up and Right branch, ru and rr. Outside of the bridge, two sub circuits are added. The first one represents the coil, its resistance r_{coil} and voltage source vs as current sensing element. The second one replaces the external magnetic field with a voltage source vm and resistor r_m = 1Ω to provide the current used in CCCS element.

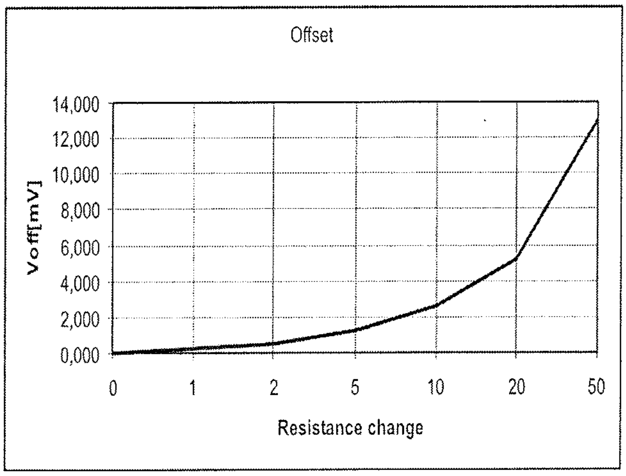

Fig. 4: Offset vs. Δrur

Relation for internal magnetic field B_{int} is given by the equation k_1B_{int}. Constant k_1 is multiplying factor for coil generated magnetic field, which contains all parameters defined by the process. This constant is basically the sensitivity of Hall element for internal field and the constant k_2 is the sensitivity of the element for external magnetic field.

Heating of the integrated coil around the Hall element due to the current flowing trough, causes signal distortion of Hall element output signal /4/. The detailed analysis of the output signal provided the parameters for modeling this phenomenon. It has been determined that relevant distortion harmonic component is the second, due to of relation between current and heating, which is quadratic (Joule losses).

In Figure 5b, the full Hall model is presented, including the heating influence generators. They are positioned in left and bottom part, to meet the modeling requirements for the design and layout. Two sub-circuits were used, to provide correct function in both positive and negative coil current. This is necessary as the negative coil current returns a zero for VRC in SPICE simulator.

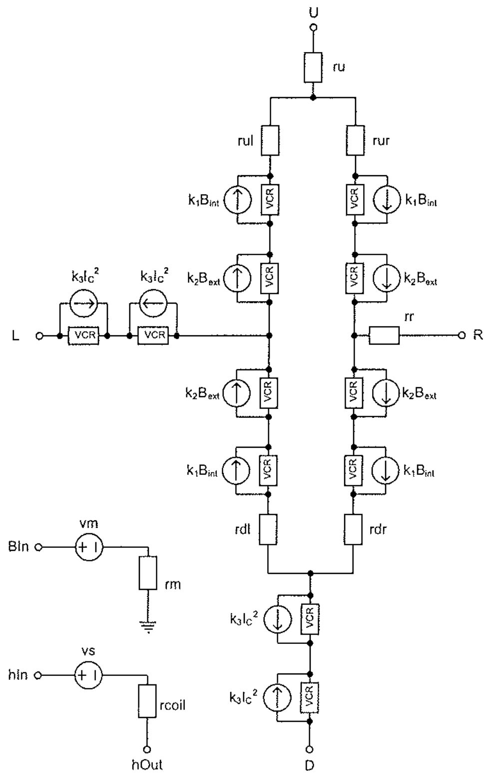

Fig. 5b: Full model of Hall element

In the time diagram (Figure 6), simulation of Hall element model is shown. All simulations are done with 0.6um CMOS technology parameters. In the upper trace the input coil current hIn is presented. The middle trace shows the output signals, in this case R and L, and the bottom trace is the difference between them. In our simulation we have 10mA of coil current and the Hall element bias current 1mA.

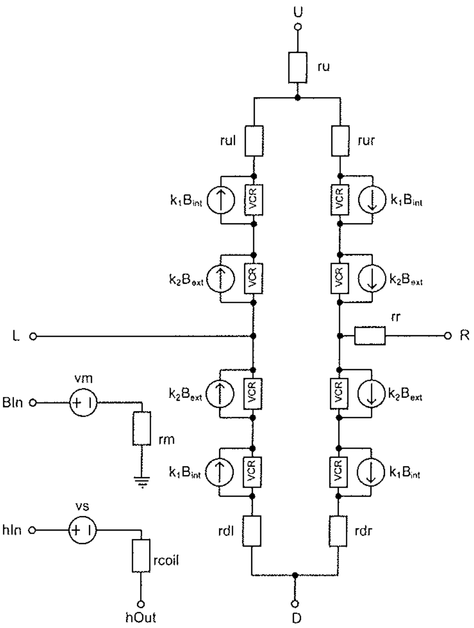

Fig. 5a: Simplified model of Hall element

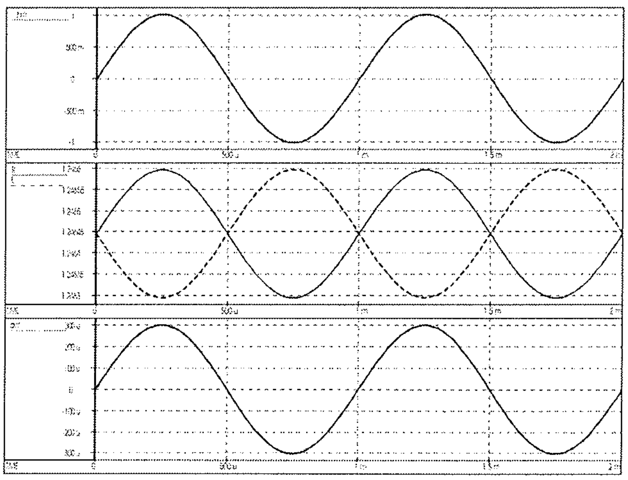

Fig. 6: Simulation result for internally generated magnetic field by integrated coil current

In figure 7 the simulation results of external magnetic field are shown. The upper trace is input Bin voltage representing external field, as voltage.1V level corresponds to 10mT of external field. As in diagram shown in fig. 7 the traces in the middle are the Hall element outputs R and L, and bottom trace is the difference between both outputs.

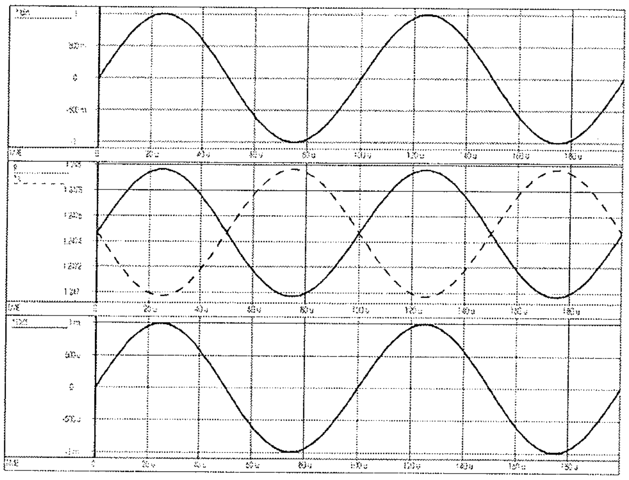

Fig. 7: Simulation results for external magnetic field

Heating effect, which is modeled by generators, is described with $k_3I_C^2$ function. Constant k_3 presents the heating factor and I_C is the current flowing trough the coil. Factor k_3 is a function of coil geometry and resistance. Simulation for thermal influence on the output was done with internal magnetic field. As shown there are distortions at peak values of each output in the middle trace on figure 8.

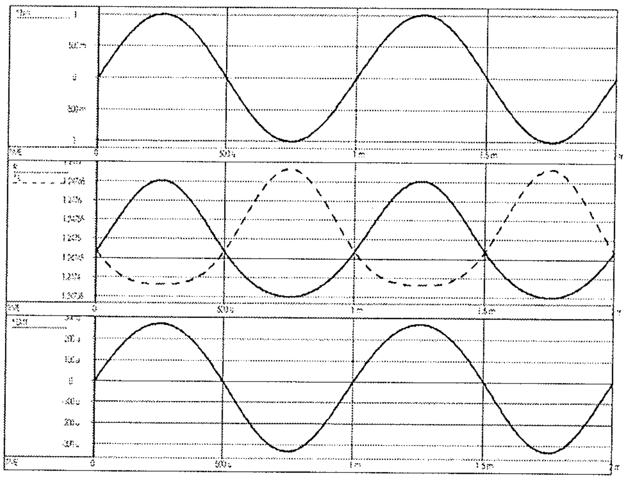

Fig. 8: Thermal effect of coil current

Differential output signal is shown on the bottom trace of figure 9. Exact mechanism of distortion effect is caused by the temperature gradient trough the element. Positive peaks are flattened and negative are sharpened, because of the second harmonic component added.

For offset voltage modeling a proposal model does not offer an user friendly simulation approach so we decided to modify the model with the offset voltage as parameter which

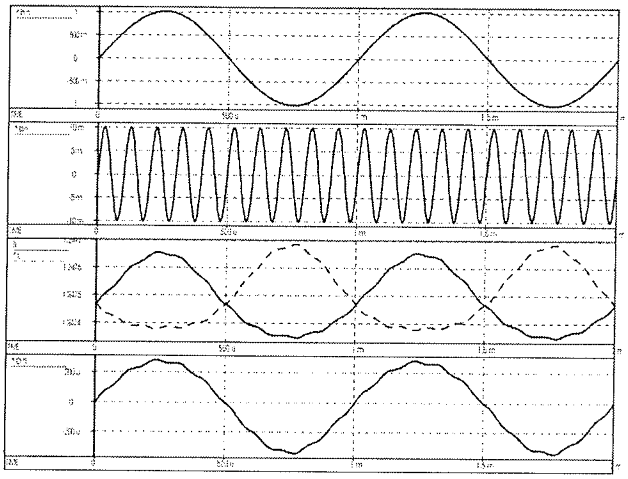

Fig. 9: Differential output signal as result of internal and external generated magnetic field

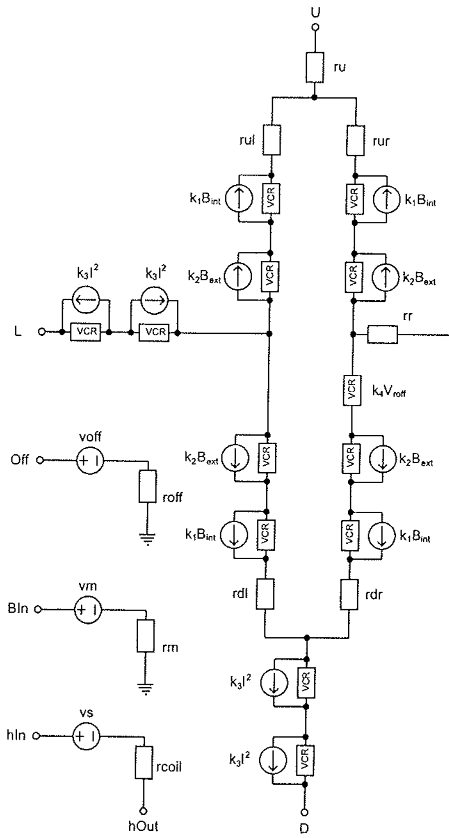

Fig. 10: Final Hall element model

can be derived from matching characteristics of process. The modified model is shown in figure 10.

We have added a VCR element, controlled by voltage on roff resistor. Additional pin was added in the model labeled as Off. A voltage source voff was included in the offset branch for supervising the current flowing trough roff resistor. Resistor roff is n-well type to take into account the temperature variations of the offset. Voltage equation k_4V_{roff} describe the offset voltage dependence on voltage on resistor Vroff. The constant k_4 is the sum of all process parameters influencing the offset voltage /2/ and is set to achieve a maximal possible offset ~ 10mV at 1V on Off pin. As the resistor roff is a n-well resistor, we can simulate temperature dependence of the offset trough voltage. The simulation shows 0.66%/K temperature coefficient of the offset voltage around room temperature, and up to 0.9%/K TC of the offset voltage in the range from -40°C to 140°C.

3 Measurement results

Measurements were done to verify the model coil heating influence on the output signal. The output voltage of Hall element was amplified with gain of 94,72.

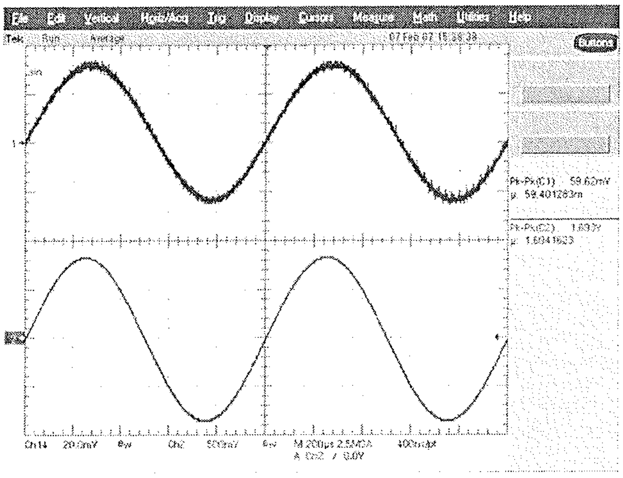

Fig. 11a:Oscilloscope picture at I_C = 5mA

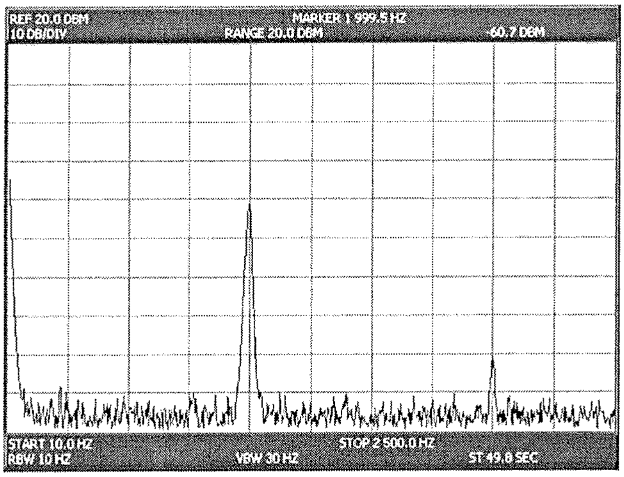

Fig. 11b:Spectral components at I_C = 5mA

Figure 11a is oscilloscope picture of the output signal shown on upper trace for coil current I_C = 5mA. For such current the distortion is not clearly visible, but it is seen in figure 11b, where the spectrum of the output already shows a second harmonic component at -38dB, compared to the first harmonic component.

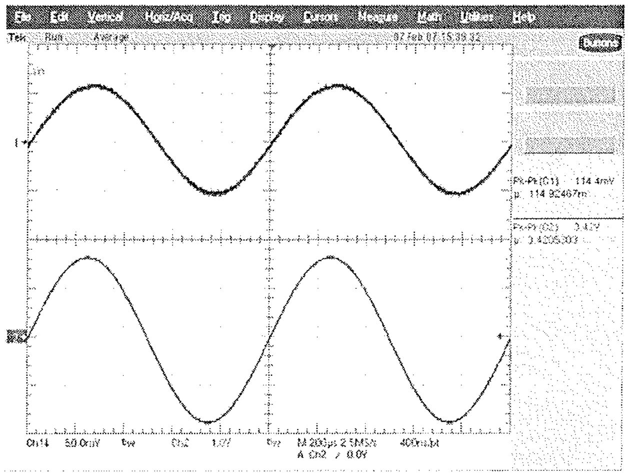

Fig. 12a:Oscilloscope picture at I_C = 10mA

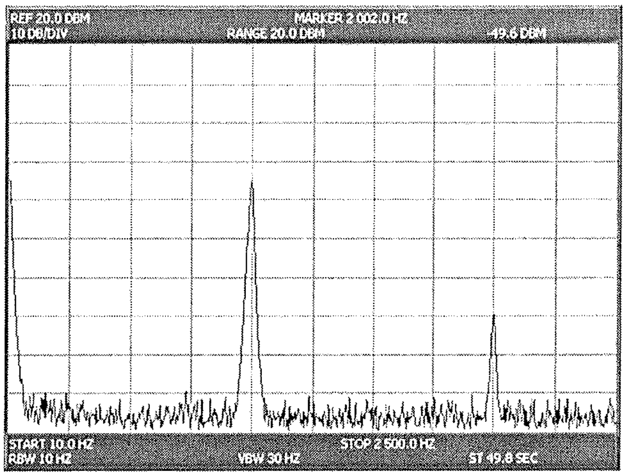

Fig. 12b:Spectral components at I_C = 10mA

By increasing the coil current to 10mA (figure 12a), the second harmonic is increased for 12dB (figure 12b), which is in good accordance to the simulation model.

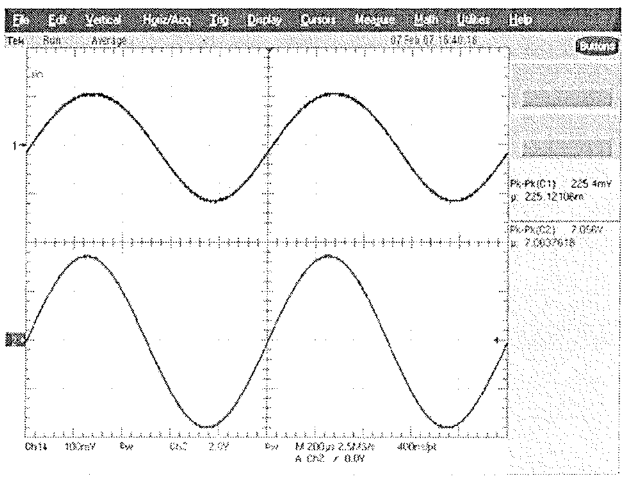

Fig. 13a:Oscilloscope picture at I_C = 20mA

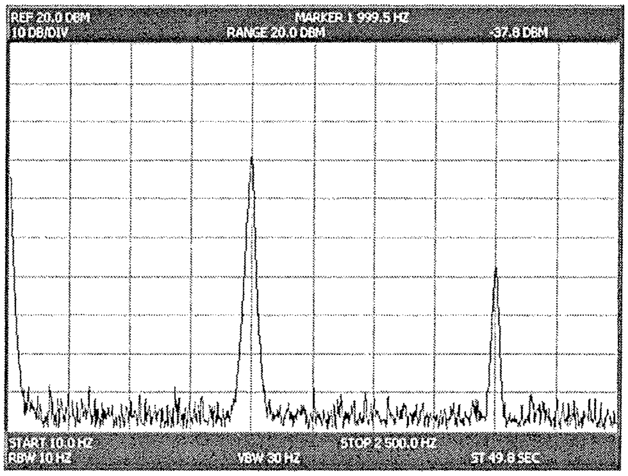

Fig. 13b:Spectral components at I_C = 20mA

Further increase of the coil current to 20mA (figure 13a) increases the second harmonic component for additional 12dB (figure 13b), as expected.

4 Conclusions

New six terminal Hall element model was developed and described in the paper. In presented model all magnetic contributions were taken into account including internal magnetic field, external magnetic field, Hall element offset voltage and its temperature dependence. In addition a distortion of the output signal due to the integrated coil heating was included in model. A measurement on Hall integrated element with coil showed a good compliance with the proposed model.

5 References

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univ.dipl.ing.el. Aleksander Sešek
University of Ljubljana
Faculty of Electrical Engineering
Tržaška cesta 25, SI-1000 Ljubljana, Slovenija
E-mail:aleksander.sesek@gmail.com
Tel:+386 1 4768 727, Fax: +386 1 4264 644

prof.dr.Janez Trontelj
University of Ljubljana
Faculty of Electrical Engineering
Tržaška cesta 25, SI-1000 Ljubljana, Slovenija
E-mail: janez.trontelj1@guest.arnes.si
Tel:+386 1 4768 333, Fax: +386 1 4264 644

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