Modelling of Bulk Current Injection Method for a coaxial cable

Uwe Stürmer[1], Gervin Thomas[1], Heiko Köhne[1], Werner John[1]

[1] Fraunhofer Institute for Reliability and Microintegration (IZM), Department ASE, Gustav-Meyer-Allee 25, 13355 Berlin, Germany, Phone: +493046403614, Email: uwe.stuermer@izm.fraunhofer.de

Abstract — **In order to make predication which effects at cables termination is caused by an inductive injected interference, a BCI-model has been developed. This paper thereby elaborates on the modelling of the cable and the BCI-clamp. This includes the skin effect and the transfer impedance between the inner- and outer conductor for cable. For the modelling of the BCI-clamp foregoing measurements were made. Those measurements allowed developing a model, which has an expanded frequency range for the BCI-clamp. To verify the model some comparative measurements were made. The measured power at the end of the cable was compared with the simulated results of the model.**

1. INTRODUCTION

In the following article a Spice model for the bulk current injection (BCI) method is introduced. With this model it will be possible to predict how intense an inductive coupling in a cable will be at the end of that conductor. Out of this it is possible to draw conclusions whether the connected device ensures his full operability. A measurement, which gives information about an interference, could only be done when the whole device is fabricated. At this point it is very difficult to correct a fault if the connected device fails. Often the only possibility is to redesign the whole device. This redesign produces a lot of costs which could be avoided with a simulation at the beginning of the design process. Therefore a model will be introduced in this article, which is able to make such a prediction. This article deals with the measurement and modelling for the BCI-clamp. Furthermore a model was developed for very short conductor compared to the wavelength. Based on that model a model for the whole cable was developed. To make a predication about the model accuracy some comparing measurements were made. Then the results from the simulation and the measurements were compared.

2. ASSUMPTION

Before the model could be developed some constraints will be made. These are done to avoid a high model complexity and to lower the required computing time. Furthermore some restrictions have to be made because of the used measuring equipment.

1.) The interference is given only on the outer conductor of the cable. From there the interference will spread to the inner conductor through the cable's transfer impedance. For every examination it is necessary that the flowing current on the inner conductor is zero. The interplay between a current flowing on the inner conductor and a voltage on the outer conductor is described by the transfer admittance Y_t. In the following model that point will be neglected. That means the transfer admittance is zero ($Y_t=0$).
2.) The complex transfer impedance is realised as a resistor with an inductivity connected in series. Therefore the transfer impedance is assumed as $Z_t=R_t+j\omega L_t$.
3.) The skin effect is only realised for the inner conductor of the cable. Because of model complexity and computing time the skin effect for the outer conductor is neglected.
4.) Measurements are only accomplished in the frequency range from 10 MHz–220 MHz. The reason why this range has been chosen is the absence of significant effects below 10 MHz. The amplifier used for the compared measurements limits the higher level of the frequency.

3. MODELLING OF THE SKIN EFFECT

The suppression of the current on the edge increases with growing frequency. In coax conductors the current flows only in a thin surface layer of the inner- and outer conductor. In literature this effect is referred to as skin effect. Because of this skin effect the longitudinal resistance increases with growing frequency and the cable longitudinal inductivity decreases.

The skin effect was realised as in [1] with lumped circuit elements.

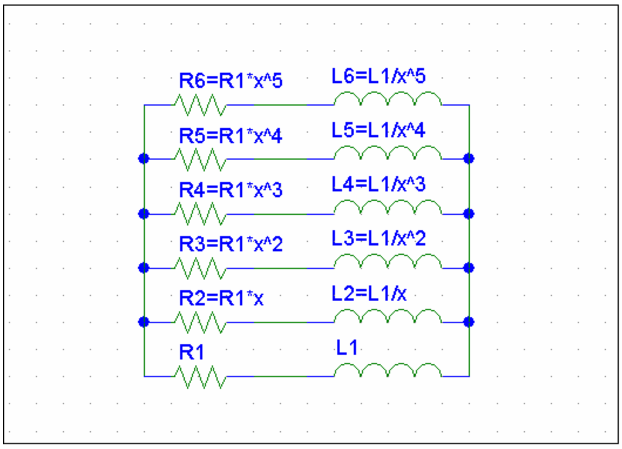


Fig. 1. Realisation of the skin effect

Fig. 1 shows the realisation of the skin effect. The values of the resistors R_n, the inductivities L_n and the factor x were chosen in reference to the guidelines in [1]. In this realisation the resistance increases with growing frequency and the longitudinal inductivity decreases.

4. MODELLING OF THE BCI-CLAMP

Several measurements had to be taken to model the signal generator, the amplifier and the BCI-clamp. In the run-up to the experiment it was known that the used BCI-clamp has a constant transfer factor up to 100 MHz. The transfer factor between 100 MHz and 220 MHz has to be determined to get comparative measurements up to a frequency of 220 MHz. Therefore a similar experimental setup to the introduced method in [2] was chosen to measure the transfer factor up to 220 MHz. A signal was produced with a generator and transferred through the amplifier directly to the BCI-clamp. With a clamp this signal was coupled inductively to a conductor with a both sided 50 Ω termination against ground. The transfer factor can be calculated by measuring the primary voltage at the input of the BCI-clamp and the secondary voltage at one of the 50 Ω resistors. Fig. 2 shows the measured and afterwards linearised transfer factor plotted against frequency. The already known constant transfer factor up to 100 MHz is recognisable. This graph is used for the model because there is no information in the BCI-clamp datasheet above that frequency. As expected the transfer factor decreases after the constant range with growing frequency which implicates a weaker coupling.

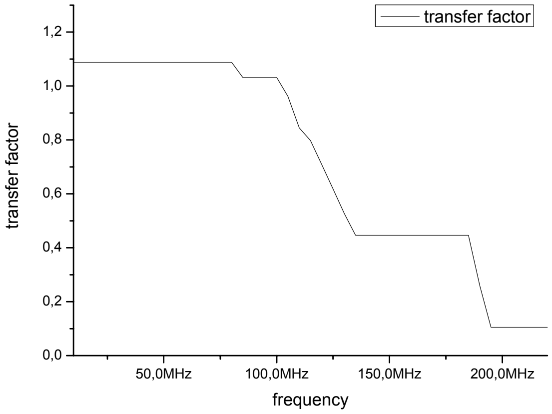
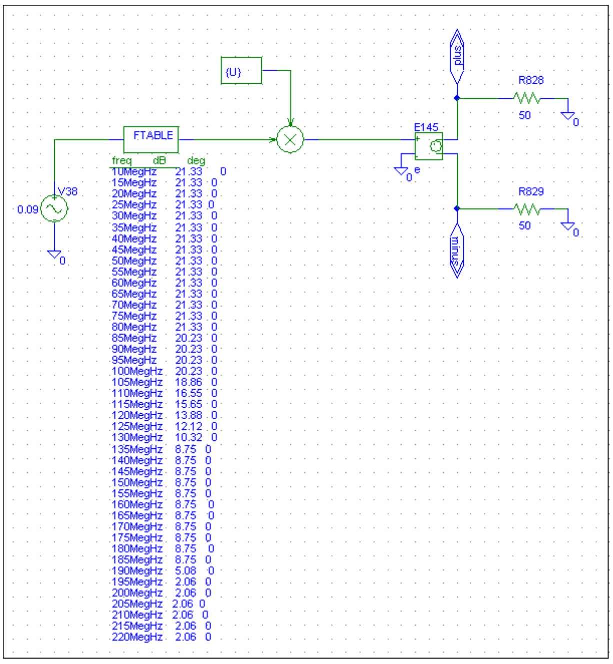


Fig. 2. Transfer factor plotted against frequency

After determining the transfer factor a Spice-Model was prepared including that factor.

Fig. 3 shows the modelling of the BCI-clamp. The model was created using PSpice circuit elements. The usage of those circuit elements can be derived from [3].

The voltage source generates a constant voltage against frequency. The transfer factor measured earlier is generated from the voltage using the circuit element „FTABLE“ by amplifying the voltage of the individual frequency ranges. This factor is now multiplied with the applied and already amplified voltage from the signal generator and amplifier with the help of a multiplier. The resulting voltage can now be coupled as interference at the corresponding place into the cable model.



freq	dB	deg
10MegHz	21.33	0
15MegHz	21.33	0
20MegHz	21.33	0
25MegHz	21.33	0
30MegHz	21.33	0
35MegHz	21.33	0
40MegHz	21.33	0
45MegHz	21.33	0
50MegHz	21.33	0
55MegHz	21.33	0
60MegHz	21.33	0
65MegHz	21.33	0
70MegHz	21.33	0
75MegHz	21.33	0
80MegHz	21.33	0
85MegHz	20.23	0
90MegHz	20.23	0
95MegHz	20.23	0
100MegHz	20.23	0
105MegHz	18.86	0
110MegHz	16.55	0
115MegHz	15.65	0
120MegHz	13.88	0
125MegHz	12.12	0
130MegHz	10.32	0
135MegHz	8.75	0
140MegHz	8.75	0
145MegHz	8.75	0
150MegHz	8.75	0
155MegHz	8.75	0
160MegHz	8.75	0
165MegHz	8.75	0
170MegHz	8.75	0
175MegHz	8.75	0
180MegHz	8.75	0
185MegHz	8.75	0
190MegHz	5.08	0
195MegHz	2.06	0
200MegHz	2.06	0
205MegHz	2.06	0
210MegHz	2.06	0
215MegHz	2.06	0
220MegHz	2.06	0

Fig. 3. PSpice-Model for the BCI-clamp

5. MODELLING OF A CABLE SEGMENT

The modelling of the used coax is based on simple equivalent networks known from the literature. The model is independent from the direction of use. This leads to the use of a T-equivalent network for the conductor. All used conductor-parameters are in value per-unit-length (p.u.l.). A qualified statement can only be ensured if every used segment represents a section that is smaller then $\lambda/20$.

The model uses the classic equivalent network. The inner- and outer conductor of the coax are each represented as a conductor. Both conductors are coupled among each other over the cable transfer impedance. Fig. 4 shows a single cable segment.

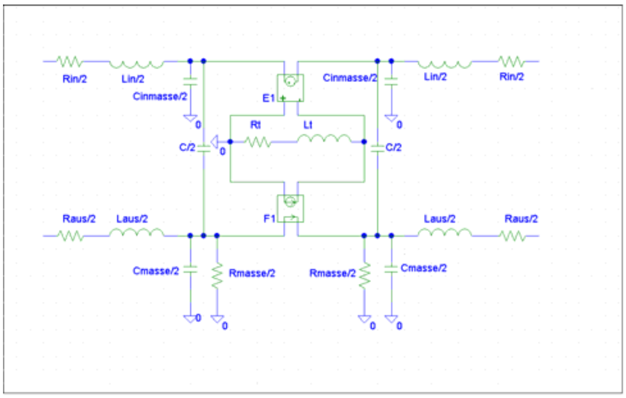


Fig. 4. One cable segment

The resistor R_{in} and the inductivity L_{in} from the inner conductor are only black boxes in Fig. 4. The whole structure of the cable segment which includes the skin effect is given when these black boxes are replaced by the circuit from Fig. 1. R_{aus} and L_{aus} represent the DC Resistance and the inductivity of the outer conductor, respectively. The skin effect is disregarded for the outer conductor as already discussed in the beginning. The capacity formed between the inner and outer conductor is given by C. $C_{inmasse}$ and C_{masse} represent the capacitive coupling from the respective conductor and ground. The Simulator PSpice does not simulate without an additional resistor R_{masse} which is parallel to C_{masse}.

The coupling between the inner- and outer conductor with the help of the transfer impedance is already discussed in [4]. The complex transfer impedance is realised with a current-controlled current source, an inductivity, a resistor and a voltage-controlled voltage source. The current flowing on the outer conductor is taken with the help of the current-controlled current source and afterwards given to the resistor R_t and inductivity L_t which are in series. Resistor and inductivity form the transfer impedance. The voltage over the transfer impedance is taken by the voltage-controlled voltage source and is given to the inner conductor.

6. FINAL MODEL

To model a whole cable several segments have to be combined. Every used segment must represent a section from the conductor that is smaller then *λ/20* to ensure the correctness. Later on the model should be used for cables up to 2,60 m. So the calculation for the minimum of needed segments will be done with a theoretical cable of the length 2,60 m.

$$\lambda = \frac{v_p}{f} = \frac{\frac{2}{3} \cdot C_0}{220MHz} = 0.908m \qquad (1)$$

$$A = \frac{L}{\lambda/20} = \frac{2,6m}{0,908m} \cdot 20 = 57.27 \qquad (2)$$

The following parameters are used: v_p cable wave propagation velocity, f maximum used frequency, L cable length, A minimum of needed segments. The calculation shows that at least 58 segments are needed to model the whole cable. For a better modelling 60 segments are used.

The model for the BCI-clamp combined with the model of the cable forms the final model. The interference from the BCI-clamp must now be coupled at the corresponding point into the cable model. Also the conductor parameters must be determined. The inductivity, the capacity between the conductors and both DC-resistances are given in the data sheet [5] from the used cable RG174. The transfer impedance phase and the magnitude are already measured in [6]. The resistance and inductivity can be calculated from those given graphs. The missing capacities and inductivities can be calculated with the help of a 2D FEM tool. The program calculates the p.u.l. parameter as well as the lumped parameter for the used model circuit elements through the creation of a cross section from the cable.

7. MEASUREMENTS AND SIMULATIONS

Some comparative measurements were made to verify the results from the developed model. The intention of the measurement is to get a predication of how intense the loss of power caused by the BCI-clamp is at the end of a coax cable. All measurements are executed in a shielded chamber. Coaxes from the type RG174 with different lengths were placed on foam 6 cm high. The cables have no DC coupling to ground. The one end of the cable was terminated with a 50 Ω resistor in its characteristic impedance. The other side was connected to a spectrum analyser with an input impedance of 50 Ω. The BCI-clamp was placed at intervals of 48 cm and 38 cm from the spectrum analyser.

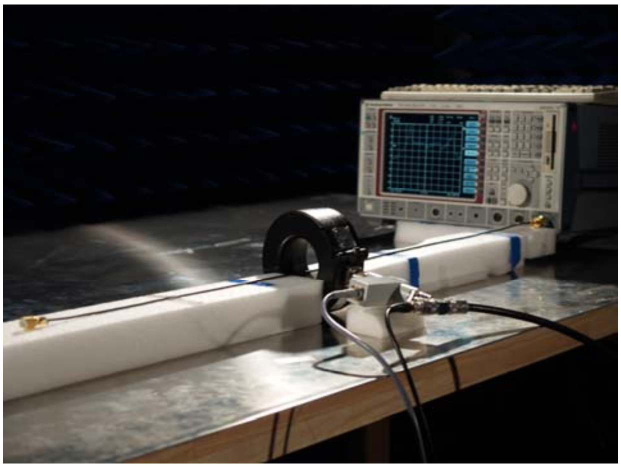


Fig. 5. Measurement set-up in a shielded chamber

Fig. 5 shows the measurement set-up in a shielded chamber. The signal generator and the amplifier are also in the shielded chamber. The signal generator was programmed to produce a sinusoidal signal. This signal was amplified and given on the BCI-clamp. The spectrum analyser shows the frequency spectrum produced from the interference. After this measurement the resistor at the left end of the cable was changed. The following resistors were used: 50 Ω, 98 Ω and 388 Ω. These measurements were executed with cables of the length 1 m and 1,80 m.

The simulation was then adjusted to the measurement set-up. The corresponding point of delivery for the interference from the BCI-clamp was calculated and integrated in the model. The lumped conductor parameters were calculated from the p.u.l. parameter for 60 segments. As in measurement set-up one resistor was changed for the simulation.

8. RESULTS AND INTERPRETATION

The first measurement was executed with a 1 m cable and a termination with 50 Ω. The point of delivery was chosen to be 49 cm away from the spectrum analyser. Fig. 6 shows a comparison between the measurement and the simulation.

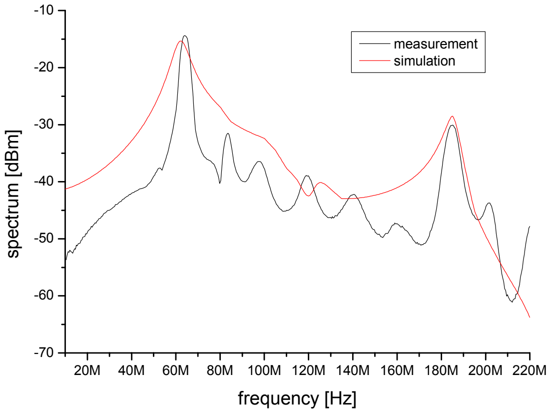


Fig. 6. Frequency spectrum from the 1 m cable with a 50 Ω termination and a point of delivery by 49 cm

It can be seen, that the simulation predicts the arising maxima. The results from the simulation are always higher than the measured results, so that the model can considered as worst case model for EMI prediction. For the next measurements the resistor was changed. The measurements show with growing resistance a reduction of the attenuation. This behaviour could also be verified in the simulations. The characteristics of the graph change only to a minor degree so that for the purpose of clarity there is no additional graph.

The second maximum was reduced by the variation of the position from the BCI-clamp. Fig. 7 shows the comparison between the measurement and the simulation with a point of delivery at a distance from 38 cm from the spectrum analyser.

The simulation shows the same behaviour like the measurement. But the first maximum now has a slightly underestimate from 3-4dbm.

For the next measurements a cable with the length of 1,80 m was used. The comparison between the measurements and the simulations shows that the maxima also can be predicted. However a strong underestimate in some ranges between the maxima was noticed.

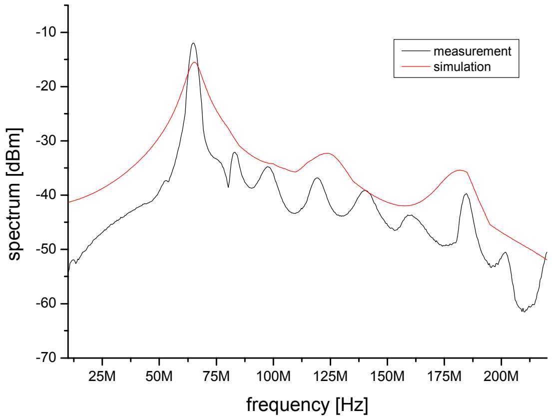


Fig. 7. Frequency spectrum from the 1 m cable with a 50 Ω termination and a point of delivery by 38 cm

These underestimates in some ranges mostly come from the BCI-clamp used for the measurements. The data sheet of that clamp gives the information that this used clamp is only designed for a frequency of up to 100 MHz. Some foregoing measurements were made to emphasise the frequency range of the BCI-clamp. Therefore the transfer factor was taken into consideration. But only a limited number of measured points for this transfer factor could be integrated in the model. The model accuracy could be increased by using more measured points for the transfer factor. But this is impossible because of the limit for the number of points embedded in the model.

9. CONCLUSION

This paper describes a methodology for the prediction of the behaviour of a BCI assembly with a coaxial cable. The model generates a covering-graph which predicts the maximum power at the end of a conductor as a result of an inductively coupled interference. Predictions could be made especially for those frequency ranges where the power maxima appear. The effect of the repositioning from the BCI-clamp can successfully be predicted. The variation of the terminated resistor could also be verified. Only the variation of the length from the used cables shows underestimates in some frequency ranges in the covering-graph.

10. ACKNOWLEDGEMENT

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