A Combined Impedance Measurement Method for ESD Generator Modeling

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Abstract—**Models of ESD generators according to IEC 61000-4-2 are required for failure simulations in order to predict e.g. the robustness of ICs or the performance of overvoltage protection elements. Due to significant variations between different generator types a flexible and fast method for individual characterization is needed. A new method is proposed here based on impedance measurements at the discharge relay and the discharge tip. A current probe for high frequencies is used as transformer to overcome the problem of missing ground reference connection of the network analyzer at the discharge relay. The measured two-port impedance data in frequency domain can be used, after de-embedding of the measurement equipment influence, to approximate a state space representation in order to create a model for time domain network analysis. The proposed method can be extended with other ports to model e.g. field coupling into wires or PCBs. The Method is presented in this paper together with a detailed application example.**

Keywords- Impedance measurement; ESD; ESD generator; ESD-modeling

I. INTRODUCTION

ESD simulation can be helpful to predict testing results and estimate the robustness of electronic systems. Different components have to be modelled. The quality of simulation results mostly depends on the precision of each single model of semiconductor, transmission path, and pulse source. Often the semiconductor is an unknown black box and modelling can be very difficult, nevertheless there are some promising approaches [1] to model the destruction behaviour of systems. The conducted pulse transmission path can be modelled e.g. quite accurately by transmission lines or PCB models. Finally simulation-based ESD testing also requires accurate models of pulse sources.

In ESD generators a network is charged by a high voltage source. The capacitance and resistance as well as the waveform are defined according to the standard IEC 61000-4-2. Often a relay disconnects the high voltage source and connects the discharge network to the discharge tip for applying a pulse. A voltage drop occurs at the relay contacts and the discharge current is flowing through the generator tip. It can be measured via a current target with low impedance of about 2 Ω with a high bandwidth oscilloscope.

In standardized ESD testing often relevant deviations between different results occur when using different ESD generators. All commercially available generator models fulfil the common ESD standards. However, there are often significant differences in the pulse shapes. Especially for discharges via other load impedances there can be quite large deviations between pulses created with different ESD generators. In [2] the waveforms of different IEC ESD pulse generators were compared. Depending on the load, deviations up to 70 % between the peak current amplitudes could be measured, although all generators fulfil the standard. This means, a single model cannot reflect the large variations between the different ESD generators.

Many simple and also complex models for ESD generators were described in literature. The highest accuracy can be reached if detailed full wave 3D models are used. The measured and simulated currents are very similar. In [3], [4], [5] and [6] the structure of an ESD generator was modelled and simulated applying the finite integration method (FIT) or FDTD. Often some structural details like the ground strap of the pulse source have to be simplified in the models in order to reduce computation time. Missing material parameters for model generation limit the accuracy further. Due to the complexity, missing material parameters, and the computational efforts of full wave models, other approaches based on lumped element model approaches are attractive. In [7] a lumped element circuit of an IEC 61000-4-2 ESD generator was derived from measurement of ESD pulses while applying many different load impedances. Although voltage and current is only available at the discharge tip, big advantages of network models are the short simulation time and possibility of combination with non-linear semiconductor simulation models. Often the value of each network element is estimated because the generator does not consist of lumped circuit elements that can be measured separately. Frequency dependent measurements of ESD generator impedances are difficult or even impossible at higher frequencies due to a missing near common reference point.

Precise models for ESD generators would help to understand different semiconductor failure levels when using different generator types. Accurate behavioural models can be generated with measurements at selected ports. In [8] an approach is presented where the relay was opened and its blade contacts were connected to a network analyser. As a second port a standardized ESD target connected to the vector network analyser (VNA) was chosen. The simulated discharge current in time domain is computed by convolution of the measured VNA data with a step function. The comparison between the waveforms obtained from this approach and the pulse shape recorded with an oscilloscope are very similar. Problem here is the connection of the VNA port at the relay that might have a significant impact on the measurement result due to undefined ground reference connection of the VNA. Ferrites used in [8] can reduce problematic cable shield currents only partially.

The characterization approach with a VNA in frequency domain is extended here. Measurements are done with a current clamp providing the necessary galvanic decoupling and overcome the problems of ferrites or differential mode impedance measurements at the relay port. Furthermore the measured frequency domain impedance data is converted into state space representation in order to create an exact model from measurement data which can be applied in any circuit simulation tools. The method can be used to characterize and create simulation models of any ESD generator type.

II. METHOD

A. *Measurement Approach*

For accurate modeling of ESD generators the impedance must be known over a wide frequency range. In real ESD generators the charging voltage can be measured between the relay contacts before the trigger closes and the voltage is reduced to zero. The current pulse shape at the relay can be calculated if the impedance between these points is known and a voltage step function is used as excitation. A similar approach was used in [8]. The impedance in frequency domain was measured by connecting a 50 Ω VNA port to the relay blades. The step response of the measured impedance data gives the time domain current shape. Arc effects in the relay can be neglected due to very short time constants. Although good results were obtained, the ground reference connection of the VNA affects the measured impedance. In fact the impedances of the ESD generator which are required for modeling are defined between the relay blades and between the tip and a metal plane. If a coaxial cable is connected to the relay and NWA, the impedance of the relay port would be changed due to the additional impedance due to cable sheath currents. Accurate characterization is not possible this way. Ferrites can help to enlarge the parallel impedance due to the cable sheath, but it is impossible to reduce sheath currents completely. Accurate impedance data can be measured at the relay if the VNA port is decoupled from the ESD generator by an RF transformer. The measurement of the second port at the generator discharge tip is a trivial problem. A 2-port S-parameter characterization can be done and a de-embedding method can be used to extract the effect of the transformer to provide the needed measurement data.

A second dataset is required representing only the transfer function of the transformer. If ABCD-parameters are used the unknown ESD generator relay impedance function can be calculated using (1). The de-embedding information of the transformer can be measured with the setup shown in Figure 1 using a VNA. With the setup shown in Figure 2 2-port S-parameters can be recorded to obtain a full characterization dataset.

$$T_{Relay} = T_{Trans}^{-1} T_{Meas} \tag{1}$$

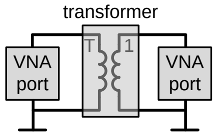

Figure 1. Setup for measurement of de-embedding data of the transformer

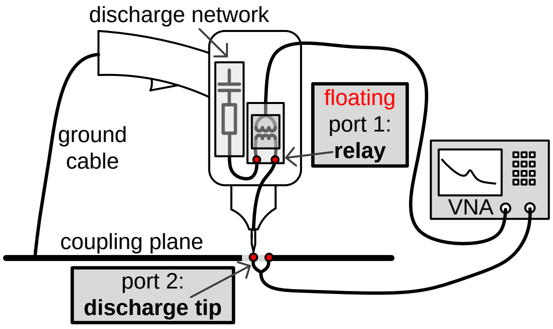

Figure 2. Measurement setup with ESD generator

B. *Measurement of Differential Ports*

Different measurement methods were possible to measure differential ports without ground connection.

1) *Differential Measurement Method with Adapter*

In [9] a technique for balanced measurement of antennas is described where two DUTs are connected via a small measurement adapter to the VNA. The VNA can be calibrated using standard two port calibration which is combined with a port extension method. Then the impedance of two identical objects can be measured differentially. In theory common mode currents are supressed if the objects are arranged symmetrically. Since the generator impedance is defined between the ESD generator and a coupling plane a rectangular reference plane was built. Two DUTs can be connected to the centre of one wing of the rectangular plane and the differential mode S-parameters can be recorded. The differential impedance is calculated from the common mode impedance. In case of characterizing pulse sources two similar ESD generators would have to be arranged in an angle of 90° to each other on the rectangular plane. The adapter endings each would have to be connected to the relay contacts of one generator to perform differential measurement. Since the dimensions of a real ESD generator are quite big the adapter endings would have to be split up at the tip for about 10 cm. This could cause inaccurate measurement results because both endings are quite far away from each other which could again cause common mode currents on the shield. Often two ESD generators of the same type are not available and the setup with a small measurement adapter seems to be more difficult to handle.

2) *Dual Transformer (Dual Current Clamp) Method*

A loop impedance can be measured using two transformers and a VNA [10]. The method allows measurement of impedance at any port where two transformers can be applied. Critical to the method is the selection of appropriate measurement transformers with sufficient bandwidth and small size. Most transformers have a very limited frequency range and cannot be used for ESD generator characterization. Here RF-current probes were used. The Tektronix CT-1 and CT-6 have sufficient bandwidth. Frequency characteristics could be removed by the de-embedding process.

In [10] the method is described how the loop impedance can be calculated from two calibration datasets and one dataset of transmission and reflection S-parameters including the wanted measurement information of the object to be measured. The network shown in Figure 3 was realized with a mercury reed-relay on a PCB.

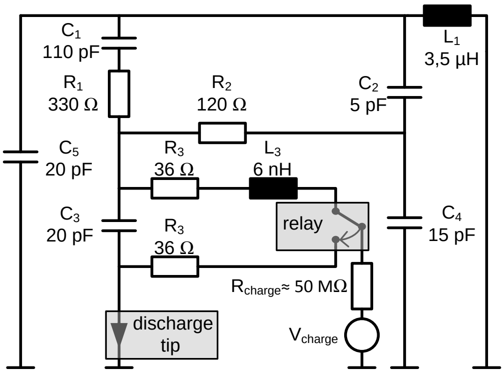

Figure 3. Approximating lumped element ESD generator network model

In Figure 5 the measured reflection Z-parameters at the discharge tip are compared to simulated data. Good results were obtained with the dual current clamp method in frequency domain which proves that the impact of the current clamps on the measured impedance is negligible. Since the resonance at about 10 MHz is very sensitive to the distributed capacitance of the circuit it could be adjusted by variation of simulation parameters. The results show the applicability of current sensors as transformer for characterization in frequency domain. The quality of the obtained impedance information depends on the recorded calibration data. In Figure 6 the time domain data of the simulated example network is compared to 3 measured pulses. The data was recorded with a 2 GHz oscilloscope and a CT-6 current probe in the discharge path. The charging voltage was 5 V during measurement. The curves are multiplied by a factor of 200 to be compared to specified values for 1 kV charging voltage. In this case the time domain waveform could not be simulated by the use of a step function from the frequency domain dataset because the voltage breakdown in the model would be simulated at the wrong position. In this method two current clamps have to be connected to the open relay contacts and two calibration datasets have to be recorded. In section III.A.1) is shown that the impact of a transformer can be extracted by using a de-embedding strategy. This means that data could be recorded applying only one current clamp to the measurement port. The impact on the impedance to be measured even would be less.

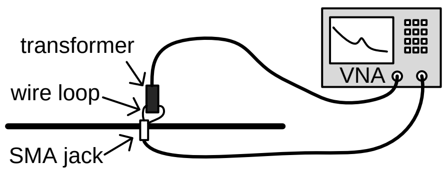

Figure 4. Setup for transformer (current-probe) characterization

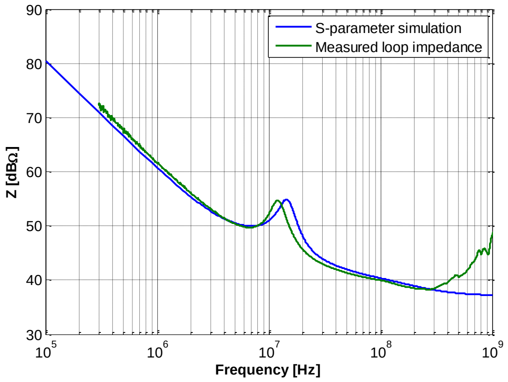

Figure 5. Simulation and measurement with dual current clamp method

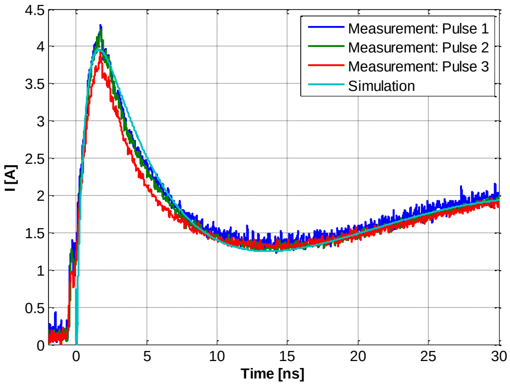

Figure 6. Time domain measurement and simulation of the example network

3) *Measurement Transformer*

As already mentioned single transformer measurements are possible in combination with a de-embedding process. First the de-embedding information has to be recorded. A sketch of the setup is shown in Figure 4. The current probe was connected to a VNA port and shorted by a wire between the inner and outer conductor of an SMA connector which was mounted on a coupling plane. The second VNA port was connected to the SMA jack to measure the transfer function of the current probe. The measured impedance and phase of the setup is shown in Figure 7 and Figure 8 for a CT-1 probe. After the transfer function of the transformer is extracted, the second 50 Ω VNA port connected to the shorted jack is seen. A phase of 0° can be measured nearly up to 1 GHz. This method is used for further investigations.

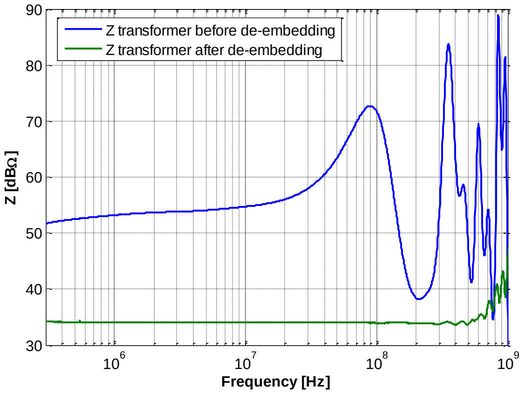

Figure 7. Measured impedance before and after transformer de-embedding

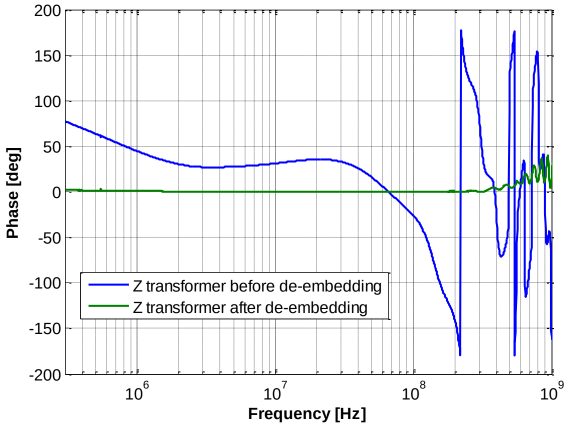

Figure 8. Measured phase before and after transformer de-embedding

C. *Behavioural VHDL-AMS Model*

The discrete S-parameters in frequency domain can be converted to an admittance representation and approximated by Vector Fitting algorithms [11] into a state space representation. The state space formulation describes the relation between input and output signals by a set of first order differential equations. It is given by equations (2) and (3).

$$\dot{x}(t) = \mathrm{A} \cdot x(t) + \mathrm{B} \cdot u(t) \tag{2}$$

$$i(t) = \mathrm{C} \cdot x(t) + \mathrm{D} \cdot u(t) \tag{3}$$

The dimension of the matrices A, B, C, and D depends on the order n of the state-space model and the number of ports p. The matrices have the following dimensions.

- A[n, n], B[n, p]
- C[p, n], D[p, p]

For a two-port system the VHDL-AMS model consists of 4 terminals P_1, P_2, P_3 and P_4. The voltage u_p and current i_p at each port is defined between the two terminals in the model architecture description (“quantity u1 across i1 through P1 to P2;”). The state variables are defined as quantities x_n of type real. Finally the state space equations can be formulated with reference to the elements of the matrices A, B, C and D.

```
x1'dot ==A(1,1)*x1 +A(1,2)*x2 + B(1,1)*u1 +B(1,2)*u2 ;
x2'dot ==A(2,1)*x1 +A(2,2)*x2 + B(2,1)*u1 +B(2,2)*u2 ;
i1 ==C(1,1)*x1 +C(1,2)*x2 +D(1,1)*u1 +D(1,2)*u2 ;
i2 ==C(2,1)*x1 +C(2,2)*x2 +D(2,1)*u1 +D(2,2)*u2 ;
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Figure 9. VHDL-AMS code for state space data

For time domain simulation the models are connected to a step function voltage source to simulate the voltage break down at the relay. The amplitude of the step function is equal to the charging voltage. The VHDL-AMS modeling process is an example. The approach can be also used in other circuit simulation environments like e.g. SPICE. Here the state space representation must be transferred into equivalent controlled current sources and impedances.

III. VERIFICATION OF METHOD

First basic investigations with a simplified network model were done to verify the proposed impedance measurement method. In section III.A the characterization method is analysed by a comparison of frequency and time domain data using the lumped element model of an ESD generator.

A. *Simulation Approach*

The standardized discharge waveform can be simulated with the circuit proposed in [8] and shown in Figure 3. A time domain simulation can be performed by setting initial conditions in the capacitor models, applying a step function voltage source, or using a DC source for charging together with a switch simulating the closing of the relay contacts. The discharge network is represented by R_1 and C_1. For the simulation setup in frequency domain port 1 is connected to the relay and a second port to the discharge tip. The impedance and phase of the configuration was simulated. The results are shown in Figure 12 and Figure 13. Up to several MHz the curves are dominated by C_1. At about 7 MHz the first minimum of the curves is obtained which is dominated by R_1 and R_3. The resonance above 10 MHz is very sensitive to small changes of the values of the distributed capacitances C3, C4 and C5 and to L_1 representing the ground strap of the pulse generator. For higher frequencies the differences between the impedances seen by the two ports become more significant.

1) *De-embedding*

Similar to Figure 1 the transfer function T_{Trans} is obtained by simulating 2-port S-parameters. For simulation a transformer model with some parasitic elements was chosen. In Figure 10 the same transformer is connected to the ESD generator circuit and the transfer function T_{Trans} is obtained. Finally we calculate the required S-parameters T_{Relay} with equation (1). Real- and imaginary parts are extracted correctly from the frequency domain data including the transformer and the ESD generator model information. T_{Relay} now is used to compute the discharge current through the tip in time domain by exciting the state space model with a step function voltage source. In Figure 11 the current shapes are compared obtained with the state space model and a time domain simulation. Small deviations can be seen at the peak of the curve due to approximation errors, but the effect can be neglected since the deviation is less than 0,1%.

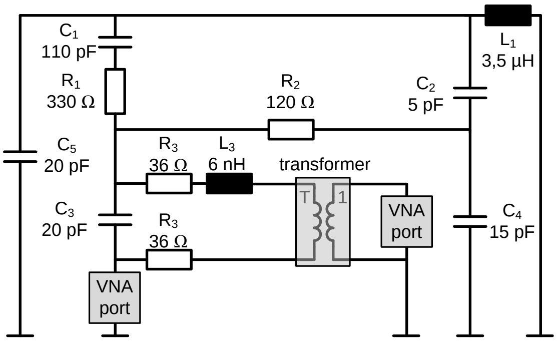

Figure 10. ESD generator circuit with current clamp

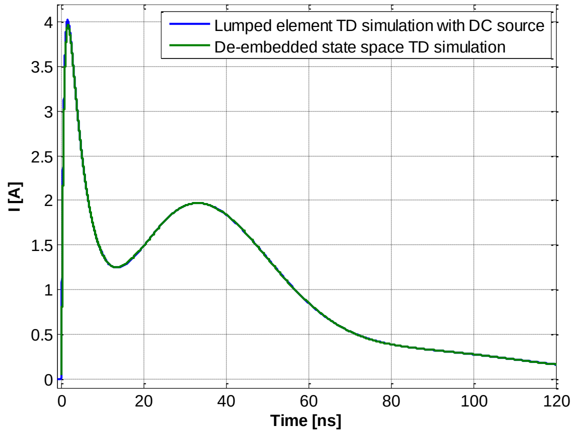

Figure 11. Comparison of the resulting pulses in time domain

IV. APPLICATION OF METHOD

The combined impedance measurement method was used for the characterization of a NoiseKen TC-815R ESD generator. To obtain the characterization data of the ESD generator the setup shown in Figure 2 was used. As the contact between the discharge network and the generator tip is realized in the relay, the measurement transformer is shorted to the relay contacts by a wire which is kept as short as possible. The generator tip is connected to the inner conductor of the SMA jack and the network parameters between both ports can be calculated using de-embedding. During measurement the ground cable of the ESD generator must be connected to the coupling plane.

In Figure 12 and Figure 13 the measured impedance and phase are compared to the simulated curves obtained from the simple ESD generator example circuit shown in Figure 3. For low frequencies the measured Z11-parameters are influenced by the lower cut off frequency of the transformer (CT-1). Up to some MHz the impedance is dominated by the capacitor of the discharge network. The curves are similar up to the characteristic resonance at about 20 MHz. The impedance at higher frequencies from about 50 MHz to 1 GHz determines the first nanoseconds of the time domain waveform. Here some differences at both ports are visible. Concerning the measured phase also a similar behavior in comparison to the lumped element simulation model can be observed.

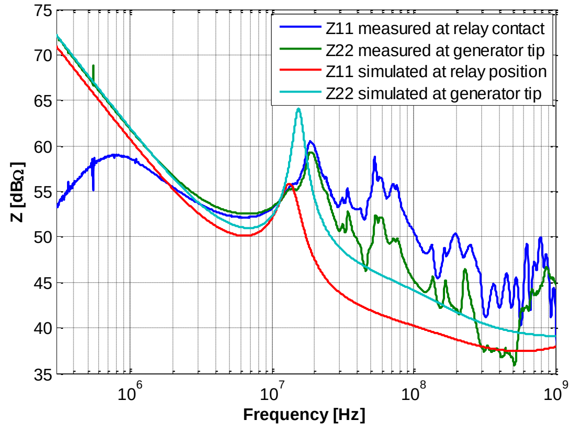

Figure 12. Comparison of measured and simulated impedance

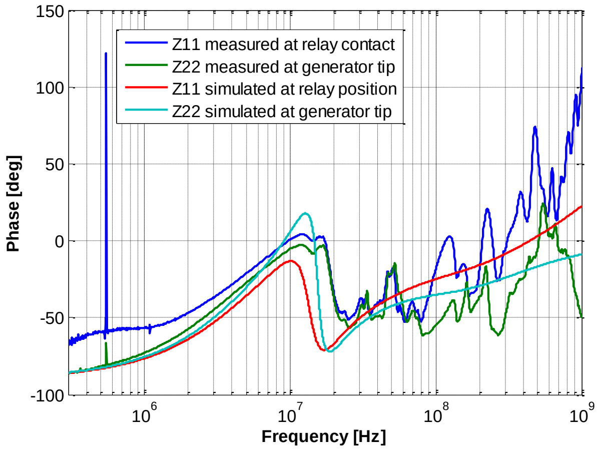

Figure 13. Comparison of measured and simulated phase

A. Modeling

A state space model was generated from the measured impedance data shown in Figure 12 and Figure 13 by using the model order reduction technique. The used model order was 24 and the bandwidth of the model was limited to 1 GHz. A good fitting can be observed in comparison to the measured data as shown in Figure 14.

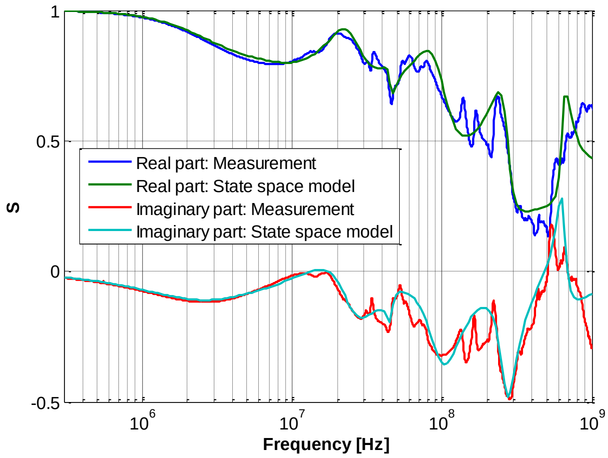

Figure 14. : Approximation of measurement data

B. Comparison of Model with Measurement Data

In Figure 15 and Figure 16 the time domain simulation from the state space model which was excited by a step function voltage source with amplitude of 1 kV is compared to measured waveforms. For time domain measurement the discharge network was charged to 10 V and the ESD generator was discharged via a standard current target. The current was recorded with a 2 GHz oscilloscope. The measurement data was multiplied by a factor 100 for comparison to 1 kV simulated charging voltage. The rise times and amplitudes of the measured and simulated first peak are in very good agreement. After 3 ns the pulses show some deviations but still keep the same tendency of maxima and minima. The allover fitting of the state space simulation model and measurement is good.

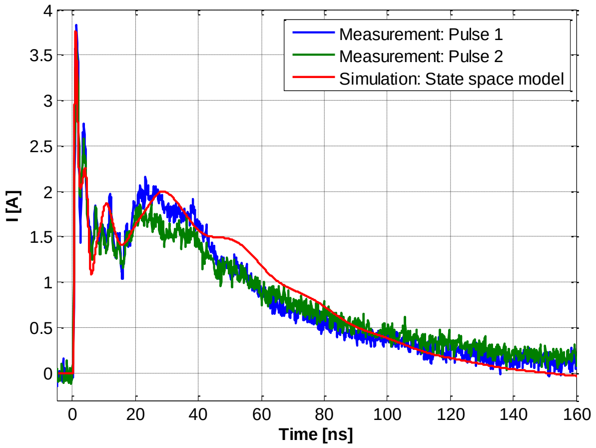

Figure 15. Comparison of measured and simulated current shapes

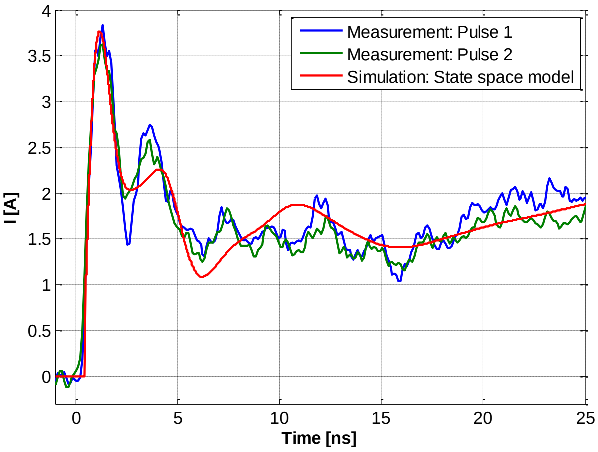

Figure 16. Comparison of measured and simulated current shapes (first peak)

V. DISCUSSION

The shown deviations are caused most likely by measurement and approximation errors. The current probe loop affects the impedance of the ESD generator relay port at higher frequencies. This might lead to inaccurate S-parameters. An extended de-embedding method could overcome this problem. At lower frequencies the signals of the current probe are very low and accuracy is affected by noise. Since the impedance is dominated by the capacitor of the discharge network the dataset used for modeling could be extrapolated.

Deviations especially at high frequencies can be important in some cases. The bandwidth for modeling ESD generators was limited here to 1 GHz due to the limited bandwidth of the applied transformer. A better transformer might solve this problem. It is also possible to characterize the ESD generator with a set of transformers for different frequency ranges. Furthermore the quality of the de-embedding information is important and accuracy is also limited here. The approximation algorithm cannot provide a perfect fitting function. Further investigations are required to understand the influence.

The proposed method that was applied to characterize an ESD generator can be also used to characterize other differential mode impedances like antennas or cable systems. For ESD this method can be extended by adding more ports to model e.g. field coupling into wires or PCBs. The state space representation also allows direct formulating of initial conditions to avoid excitation of the model by using an extra step function voltage source.

SUMMARY

Individual and accurate models for different ESD generator types are needed for virtual ESD testing. A new method for ESD generator characterization and modeling was developed. The method allows impedance measurements in a wide frequency range at floating ports, like the relay connectors of the generator. An ESD generator behavioural model for time domain simulation can be generated from the measurement data using approximation methods. The measurement method was applied to a NoiseKen ESD generator and a model was created. Comparisons have shown that the model represents very well the individual pulse shape and the source impedance of a characterized ESD generator.

ACKNOWLEDGMENT

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