Circuit Models for ESD-Generator-Cable Field Coupling Configurations Based on Measurement Data

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***Abstract*—. Accurate and flexible modeling of field coupling from ESD sources to cables or PCB traces (indirect ESD) is important for immunity estimations. Accurate circuit models can be obtained by applying approximations techniques to measurement data in frequency domain. In this paper an accurate ESD generator model is extended to model ESD coupling behavior for the ESD generator to a cable setup. The new model can be used for simulation of arbitrary load conditions, for both direct and indirect discharge. The model represents the individual characteristics of an ESD generator without applying complex 3D field simulation. It allows computation of the coupled voltages over linear or nonlinear termination using a circuit simulator.**

Keywords- ESD; ESD generator; ESD modeling; ESD field coupling; indirect ESD; ESD soft error; impedance measurement

I. Introduction

Indirect ESD can disturb or destroy electronic systems. Often voltage or current spikes at IC inputs are caused by ESD occurring in the immediate vicinity to systems or cables, without galvanic connection. Due to the very short rise times and fast changes of high positive and negative peaks, soft and hard errors of applications like automotive communication systems can occur.

The immunity to ESD coupling can be tested using an ESD generator which is discharged on a coupling plane or housing [1],[2]. In the testing standard ISO 10605 a powered-up test for indirect ESD is described. An ESD generator is discharged at different discharge points of a copper strip which is separated from the coupling plane by 5 cm dielectric material. The DUT is located at one end of the strip and connected to a wiring harness placed on the strip. Due to long wiring harness of more than 1,5 m and the short distance to the strip where the ESD current flows, high voltage and current spikes are conducted to the DUT. Furthermore, some automotive manufacturers request a special ESD test for LIN transceivers where the ESD generator is discharged via the shield of a coaxial cable and the IC is connected to the inner conductor.

For system level ESD tests the waveform of pulse generators is specified in direct contact discharge mode. Characteristic rise time and amplitudes of the current pulse are measured with an oscilloscope via a current target with low impedance of about 2 Ω [1][2]. Case studies on the comparability have shown that deviations in failure voltage levels of more than 70 % between different IEC ESD generators can appear [3]. This means that for accurate ESD simulation, models of ESD generators should be used representing the individual characteristic.

In case of indirect ESD testing, field coupling characteristics of ESD generators are important. Investigations on the reproducibility of indirect ESD tests indicate a significant dependency of testing results on the IEC-ESD generator brand and type [4]. Individual 3D full wave models were developed considering constructional details of the ESD generator [5][6].

Modeling field coupling from ESD sources to victim components using 3D simulation is still a very time consuming task. For practical work often only simplified simulation models are applied because computation time is drastically increased by any added model detail and finer discretization of structures, especially if victim components are small. Taking into account nonlinear IC models is more or less impossible.

To decrease simulation time and to consider nonlinear terminations hybrid methods were developed where fields of an ESD generator first can be estimated at a desired position of the DUT and then be introduced into fast circuit simulation [7]. Other approaches were presented, where induced currents are calculated by FDTD, if the discharge current is known [8]. But still several simulation tools are needed and data processing is complicated.

Often a special testing setup as described e.g. in the ISO ESD standard is used for several devices. Here simulation can help to estimate the robustness to indirect ESD of systems in early development steps. Models of ICs, ESD protection elements and traces can be developed and simulation of ESD robustness is possible [9]. Calculation of coupling voltage and current of an indirect ESD event in conductors mostly is required only at some cable ends where the devices are connected. In this paper an ESD generator modeling approach is extended by a coupling structure, e.g. a cable. The new model can be used for discharge analysis into multiple loads for both directly conducted and field coupled signals.

A characterization method for ESD generators, described in [10], is therefore extended for modeling indirect ESD events, considering the individual field coupling characteristic. Model generation from frequency domain measurement data is described in section II. As an example setup for indirect ESD testing a typical ESD generator – cable configuration is modeled in section III. The generated model is used to simulate a configuration where ESD fields couple into a cable and disturb an IC input.

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II. Characterization of ESD Generators

ESD generators in contact mode can be modeled based on the characteristic impedances at and between two ports (Figure 1). The discharge tip (Port 2) and the position where the voltage drop occurs (Port 1) must be considered.

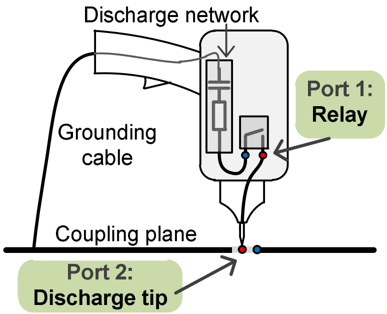

Figure 1: Ports to be characterized for discharge analysis

The port impedances of the device have to be measured or be computed by a 3D field simulation. Due to the floating relay in ESD generators measurement is problematic. In general measurement of the impedances between two ports can be done using a vector network analyzer (VNA) in frequency domain. This widely used technique works well if the calibrated VNA ports are connected to device ports which share the same RF-ground. In case of the ESD generator, the relay is far away from the discharge tip. A direct connection of the relay blades to the VNA port would change the measurement result because of sheath currents on the measurement cables. Decoupling of the ports is required. Using a potential-free measurement transformer can be a solution.

A. Floating Port Measurement Using one or two Current Probes

As described above for modeling of ESD generators the impedance information is required at least at two ports. For the relay port a potential-free method is required.

In [11] and [12] was shown that current sensors can be used for potential-free measurement of impedances with a VNA. Here two sensors are connected to the measurement instrument, one sensor acts as injecting and the second as sensing device. Both sensors therefore have to be connected to a wire which forms a part of the setup. The impedance is calculated from measured transmission and reflection S-parameters based on a Thevenin equivalent circuit representing the setup. In circuit simulation an ideal current sensor can be drawn as controlled voltage source combined with an impedance. According to the Thevenin theorem a combination of voltage sources and impedances can be transferred into a single voltage source and serial impedance. In Figure 2 Z_{setup} and V_M represent the Thevenin elements of the two current sensors and Z_x is the required impedance. For calculation of V_M and Z_{setup} two equations are required which are obtained during calibration by replacing Z_X by known values like a short or 50 Ω.

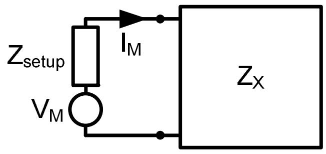

Figure 2: Thevenin circuit for measurement of the loop impedance

When transmission S-parameters should be measured between a sensor and a second common VNA port as shown in Figure 3, Z_{setup} and V_M become different and other calibration data is required than for measurement of reflection parameters where a second current sensor is used as injecting device.

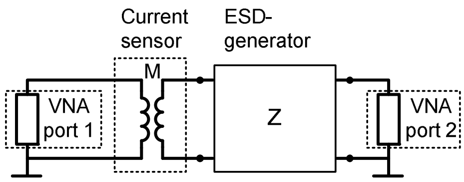

Figure 3: Measurement setup using one current probe

The problem of using different calibration data for measurement of reflection and transmission parameters could be overcome by application of a single current probe and a de-embedding method. In [10] a floating port impedance measurement method with one current sensor acting both as injection and sensing device was introduced. The transfer function of the sensor can be measured with a separate 2-port loop setup shown in Figure 4. The VNA ports each consist of the 50 Ω reference impedance and a voltage source V_s. VNA port 1 is connected to the coaxial connector of the sensor and a short wire loop penetrating the sensor hole is connected to the second VNA port.

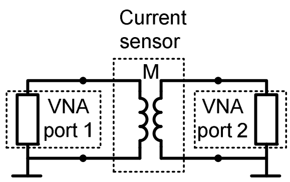

Figure 4: Measurement of current probe transfer function

Measured reflection and transmission parameters are stored in a 2-port S-parameter dataset. Due to the characteristics of the current sensor, the measured impedance data of the floating port is transformed. In order to obtain the S-parameters of the floating port, the current sensor transfer function must be extracted. During the de-embedding process the influence of the current sensor represented by the measured transfer function is removed from the reflection and transmission parameters at the relay port. Reflection parameters at other non-floating VNA ports are not affected.

In both floating port measurement setups using one or two current sensors the small connection wire between the port nodes forms part of the setup. The impact on the measurement result can be neglected since the wire is very short regarding the spectrum. In this paper the measurement method using a single current sensor is applied.

B. Multi-Port Modeling of ESD generators

In the following sections a modeling method for ESD immunity analysis, including field coupling, is described. According to Figure 5 there are 3 basic steps. First measurement data is recorded. Depending on the measurement method, additional data processing has to be done before model generation with approximation methods. The created model can be used in circuit simulators.

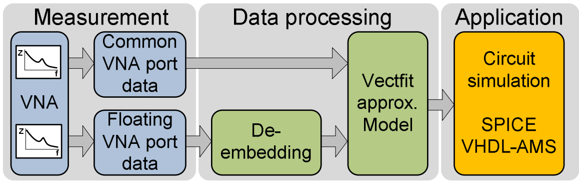

Figure 5: Proposed modeling method

The measurement setup used for modeling the discharge current is shown in Figure 6. A short wire is connected to the relay blades and the impedance is measured via a small current sensor acting as transformer.

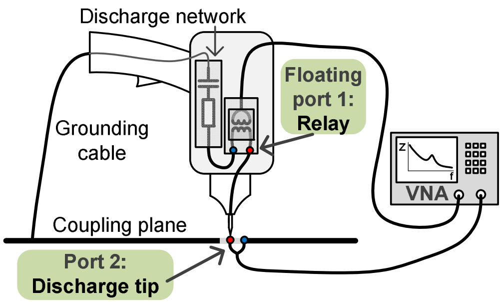

Figure 6: Measurement setup for modeling the discharge network

For modeling the contact discharge of an ESD generator, impedance data is required from two ports. In Figure 7 one floating port is considered at the relay using a current clamp as measurement transformer. Once the sensor`s response was measured the relay impedance can be calculated [10]. The second VNA port is connected between the discharge tip and the coupling plate. Field coupling between the ESD generator and other structures is modeled using additional VNA ports. In the example in section III a terminated cable is connected at port 3. If required, two VNA ports could be connected to the cable to include variable load conditions at both cable ends in simulation model. More ports could be added for modeling ESD coupling into more complex components like cable bundles or complex PCBs.

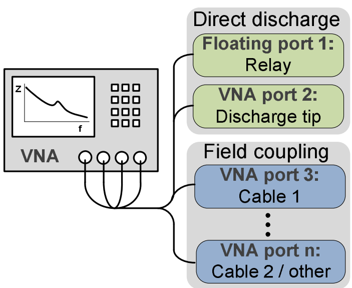

Figure 7: VNA ports for measurement

C. Behavioural Model

Measured and de-embedded n-port S-parameters are approximated to polynomials by the vector fitting algorithm Vectfit [13]. A state space representation is computed and translated for the use in circuit simulation tools like SPICE or VHDL-AMS.

The model can contain a large number of ports as measured with the VNA. Only numerical issues of approximation algorithm or used circuit simulator limit the complexity. In the circuit simulation scheme shown in Figure 8 the relay port is used for excitation and taking into account the charge voltage V_0. The second port representing the discharge tip is connected to victim circuits for contact discharge simulation. Port 3 and all other ports are used to simulate field coupling behavior to other circuitry.

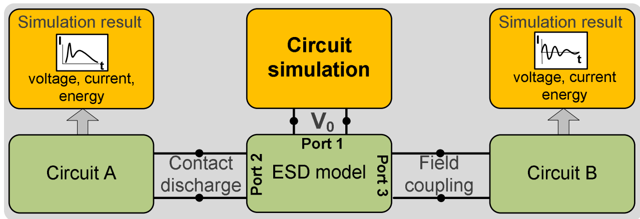

Figure 8: Circuit simulation chart

III. ESD Coupling Models for Cables

The method is verified on the basis of an example setup shown in Figure 9. A 3-port ESD generator model for direct discharge and field coupling was created.

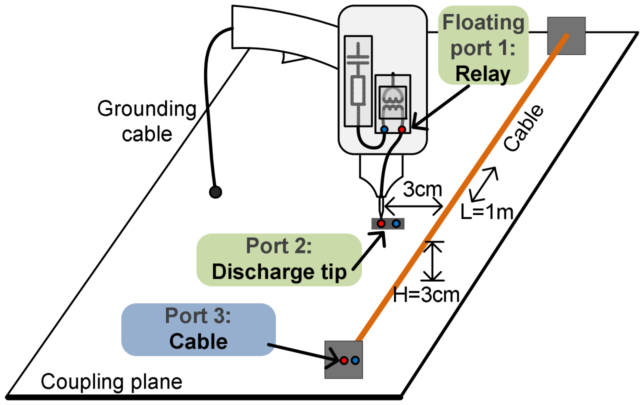

Figure 9: Setup for impedance measurement

In the setup an ESD generator is discharged on a coupling plane. Over port 1 the charge voltage is adjusted by a step function. Port 2 is connected to the discharge tip. The 3rd port allows simulation of an indirect ESD into a blank cable which is located 3 cm above the ground plane. For measurement the cable is mounted between two metal brackets with good connection to the ground plane. The ESD generator is discharged at distance of 3 cm from the cable and at half of the allover cable length so that there is 50 cm left to each end of the cable. Modeling is performed from measurement data using the characterization method described in section II. The floating port 1 is measured using a CT1 current sensor as transformer. Port 2 and 3 are directly coupled to the VNA connectors.

A. Direct DischargeModel

The full 3-port S-parameter dataset includes the impedance information between the relay blades and discharge tip. The ESD generator model is excited at port 1. The simulated time domain response at port 2 is shown in Figure 10 for a discharge into 50 Ω resistor and a charge voltage of 30 V. The simulated curve correlates well with measurement data recorded with a 6 GHz oscilloscope. The model is linear and can be scaled for any charging voltage. The curve obtained from simulation of a discharge into 2 Ω resistor is according to the IEC requirements concerning pulse rise time and amplitudes. This was shown in [10].

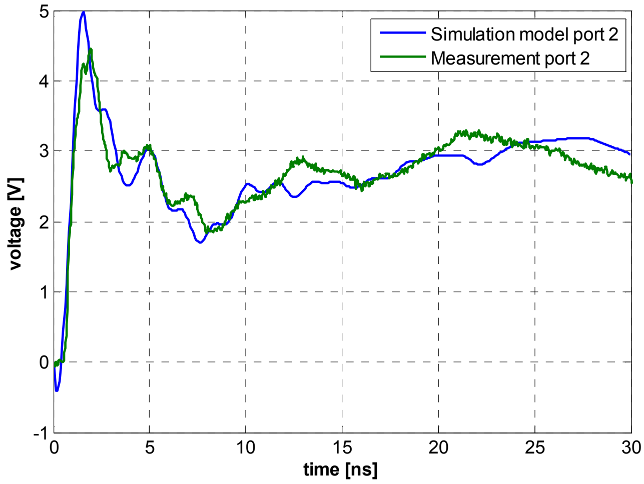

Figure 10: Measurement and simulation of ESD generator discharge current into 50 Ω

B. Indirect Discharge Model

The approximated model responses at the relay, discharge tip and the transmission line are given in Figure 11 and Figure 12. The fitting algorithm works well for the measured data. The model order is 60. Results are exemplarily shown for a transmission line terminated by 50 Ω on both ends.

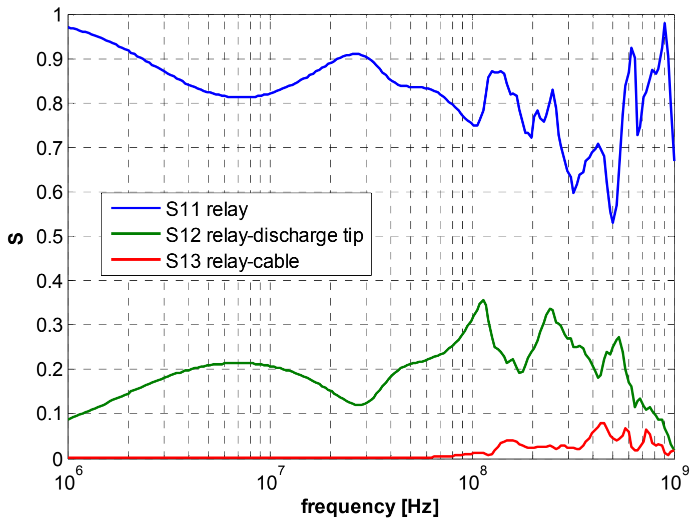

Figure 11: Model data at relay

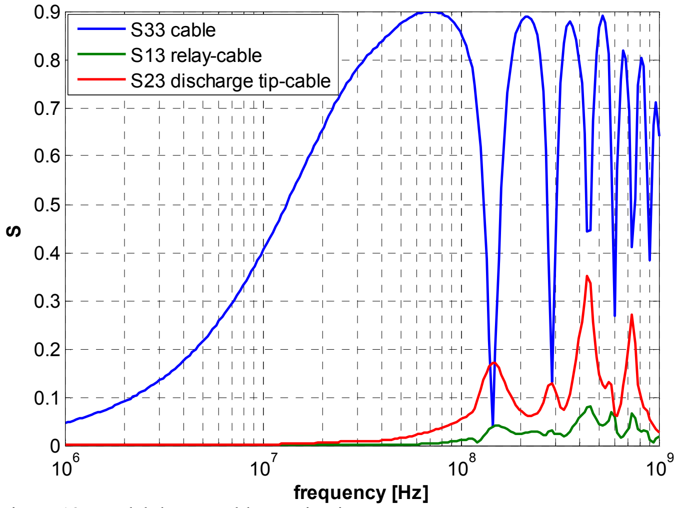

Figure 12: Model data at cable termination

As expected, coupling is stronger between the relay and discharge tip than between ESD generator and cable which is represented by S_{12}-, S_{13}- and S_{23}-parameters. Main contribution to coupling between the ESD generator and the transmission line is given by the S-parameter dataset S_{23}. In comparison the relay port 1 is more distant from the transmission line. Nevertheless coupling from port 1 to port 3 is considered in the measurement and simulation model. Comparison of S_{33}-, S_{13}- and S_{23}-parameters indicates that coupling between the ESD generator tip and the transmission line is maximal at resonances of the wire.

C. Indirect ESD for Different Load Conditions

The cable affected by indirect ESD can be terminated by different loads. To verify the applicability of the method for different load conditions, three load conditions for the transmission line were measured and modeled. Indirect ESD can be simulated for components connected to the 3rd port if the other end of the cable is left open, shorted or terminated by 50 Ω.

For verification time domain simulation is compared to measurement of ESD coupling with an oscilloscope at port 3 as shown in Figure 13. In the setup the transmission line, which is located at 3 cm from the discharge point, is terminated by the different loads at one end and by the 50 Ω internal impedance of the scope on the other end.

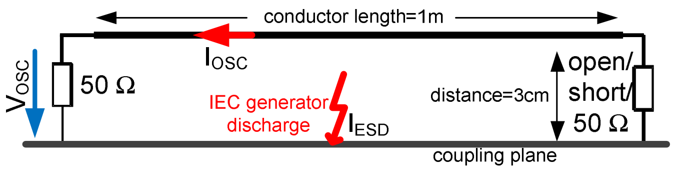

Figure 13: Measurement setup with different load conditions

For measurement and simulation the charging voltage of the ESD generator was set to 30 V. The waveforms are compared for an open and shorted cable in Figure 14 and Figure 15. The 50 Ω case is shown in Figure 16. Curve shapes of simulation and measurement are very similar in all three cases.

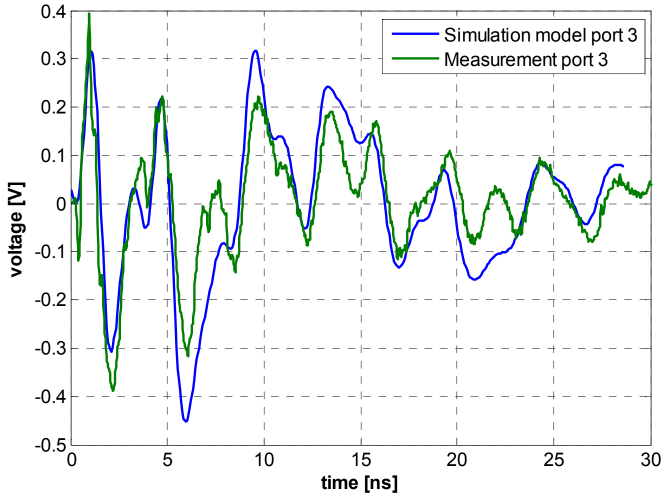

Figure 14: Measurement and simulation for open cable

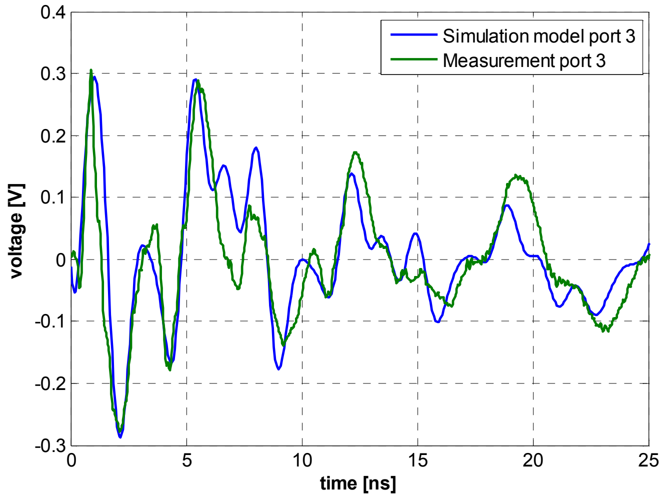

Figure 15: Measurement and simulation for shorted cable

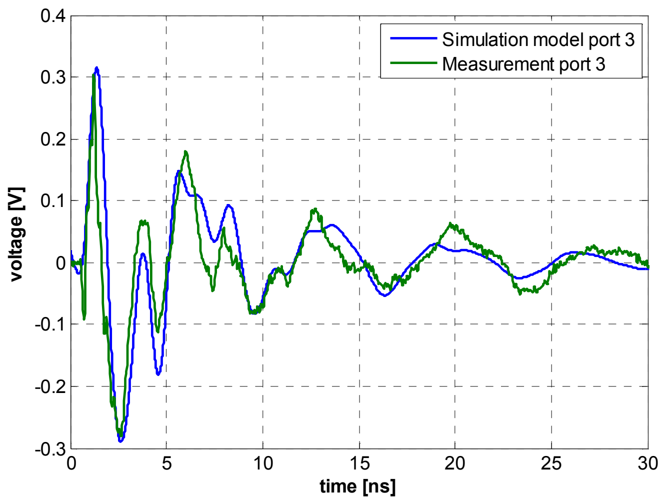

Figure 16: Measurement and simulation for 50 Ω termination of the cable

IV. APPLICATION

The models created in section III can now be used for simulation of indirect ESD testing. A discharge into the coupling plane is simulated. Current and voltage due to field coupling between the ESD generator and a cable terminated by 50 Ω are simulated for different circuits connected to the cable shown in Figure 17 and Figure 18.

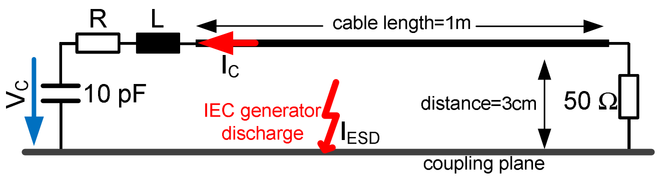

Figure 17: Cable terminated by linear elements

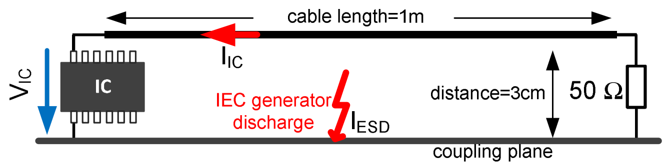

Figure 18: Simulation setup with IC model

A circuit consisting of serial resistor, inductor and capacitor can be used to estimate possible disturbances of communication systems by ESD fields. Voltage over a 10 pF capacitor circuit and a more complex IC model [9] is simulated. The more complex IC models represent pins of a CAN-transceiver and a µC. Input capacitance in both models is assumed to be voltage independent. The size for the µC-input pin is 7,6 pF and 10,5 pF for the CANH-pin.

Voltage and current shapes are simulated for 5 kV charge voltage over the input capacitance of the model. Waveforms for two configurations with IC models and another one with serial RLC circuit are given in Figure 19. The coupled voltage pulses can be large enough to cause malfunction.

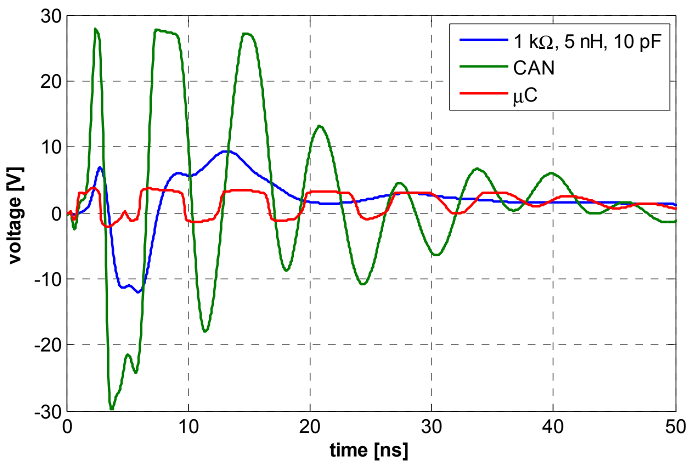

Figure 19: Voltage waveform at capacitor for 5 kV charge voltage

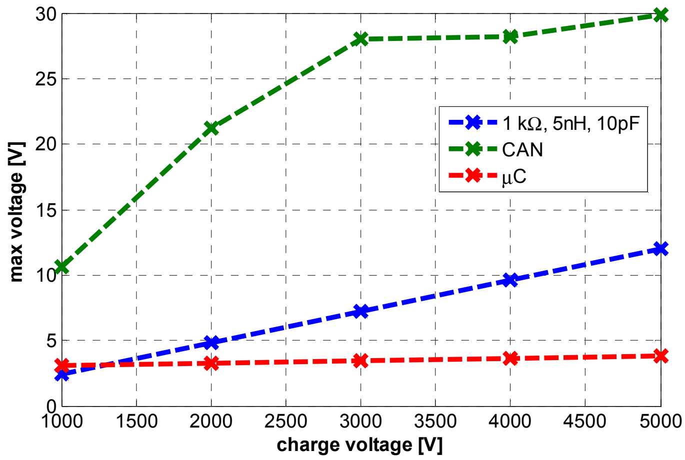

Figure 20: Peak voltage at input pin capacitor over charge voltage

In Figure 20 the coupled voltage amplitudes are shown over the charge voltage. Amplitudes increase with charge voltage level of the ESD generator. An assumed critical level of 10 V is exceeded for RLC-input at 5 kV charge voltage.

V. Discussion

The described modeling method can be applied to any coupling structure where S-parameters can be measured or simulated. Modeling of complex configurations like coupling into PCBs or cable harness topologies is possible. Any kind of linear and nonlinear termination that can be handled with a circuit simulator can be treated.

Model accuracy is good for many practical problems. Nevertheless, some problems can be observed. Problems can be separated in measurement, approximation, and simulation problems. The following measurement problems could be identified:

- Frequency range of available current probes that can be used as measurement transformers is limited. More than 1 GHz is difficult to reach today.
- Impedance range to be measured is very large. Accuracy of VNA for low and very high impedances is low. This can affect the measurement data quality.
- Calibration of measurement setup is difficult. Current probe transfer impedance must be measured and the needed setup affects the results. Additional de-embedding techniques can be used, but complexity will increase.

Approximation techniques are still under research. The proposed simulation method is affected today by the following problems:

- A large frequency range can be difficult to approximate. Deviations cannot be avoided.
- More than 6 ports are often difficult to handle.

Furthermore large approximation models can cause convergence problems in circuit simulators. Finding appropriate simulator settings can be a time consuming task or even impossible.

Summary

A new modeling method for simulation of direct and indirect ESD coupling was presented. A potential free measurement method was introduced to obtain the impedance information at the ESD generator relay. The impedance information is obtained by de-embedding. The method was applied to an ESD source – cable configuration. Coupling of an ESD event into a cable was investigated with complex nonlinear terminations. All simulation results were verified by measurements in time domain. Different load conditions at the discharge tip and the transmission line can be simulated in an easy way.

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