Determination of Critical Coupling Parameters Using Inverse Methods

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***Abstract*— This paper deals with different methods to find systematically critical coupling configurations. A critical coupling configuration can appear between a cable and an antenna or cables for data and power transmission. In the later case the minimum distance between the cables or the maximum length for placement in one cable bundle must be determined. One option to find the critical parameters can be standard circuit simulation. In this case the simulation has to be repeated several times. A better approach is using a direct inverse method based on the Modified Nodal Analysis (MNA). Both approaches are discussed in this paper and critical coupling parameters are determined for several configurations.**

Keywords - MNA; inverse method; transmission line; disturbance

I. INTRODUCTION

Determination of critical coupling parameters can be seen as a standard EMC problem. Systematic approaches are rare. Mainly trial and error approaches are used.

One example for a critical configuration can be the coupling between a cable carrying a time varying signal and an antenna. It can be necessary to change the shape of the cable signal to fulfill EMC demands. Here it would be interesting to find the optimal signal shapes having frequency contents exactly below the limits. The shape of the signal is here the critical parameter and has to be found [1].

Another example for a problematic coupling can be the electromagnetic disturbance from cables between a DC/AC inverter and the electrical engine, carrying pulse modulated high voltages [2]. Bus cables running in parallel might be influenced and data transmission could be corrupted. Therefore the critical coupling thresholds that ensure safe data transmission have to be determined. The determination of the shape of an interference source is not the question, because the shape of the inverter signal as the most critical parameter is given, whereas the distance between the HV cables and the data bus can be the interesting critical parameter and has to be determined.

Additionally, many more configurations can be found, where the shape of the interference source or the distance between coupling structures are the critical parameters.

One computational method to find critical parameters can be using standard circuit simulation and finding the parameters with several trials by iterative approaches. In this case the simulation has to be repeated several times to find the threshold value by searching algorithms [3]. The optimization can require complex search algorithms if taking into account multiple criterions. Convergence cannot be ensured and the computation time can be extremely long. The pros and cons of this method are discussed in this paper.

A better approach presented here is using direct inverse methods. When a coupling problem can be formulated as electrical network the Modified Nodal Analysis (MNA) can be used for the analysis. Standard formulation of MNA computes the nodal voltages of a circuit, whereas circuit parameters and excitation are given as input. For finding critical coupling configurations standard MNA cannot lead towards a direct solution. Critical excitation pulse shapes or coupling parameters can only be found by using searching algorithms. A direct solution would require providing a maximum permissible node voltage as input. A circuit parameter or an excitation pulse shape have to be found. Such an inverse circuit simulation method based on MNA can be formulated. Implementation details and applications are shown here.

The conventional method, based on circuit simulation and search algorithms, and the inverse circuit simulation method are discussed in this paper. Critical coupling parameters are determined for several configurations.

II. METHODS FOR DETERMINATION OF CRITICAL COUPLING

In this section the two methods for the determination of critical coupling thresholds are described. The first method is based on standard circuit simulation. It is discussed based on an example. The minimal distance between transmission lines and the maximum length of the lines has to be found. The problem is solved by repeating the simulation for several distances and lengths. The second method introduced here is a direct inverse method to determine a voltage shape according to a critical limit that can be given even as voltage over frequency.

A. *Optimization Method*

As introduced above, one method to find critical coupling parameters like maximal length or minimal distance of parallel cables is to simulate the data signal integrity. An example for such a configuration is given in Figure 1. Here the coupling between a three phase HV cable and a communication bus cable has to be analyzed. The simulations have to be repeated for different lengths and distances. With the computed results it is possible to find minimum or maximum values. To do the simulation, precise models of the employed components like the multi conductor transmission lines, transceiver, DC/AC inverter, electrical engine etc. are needed.

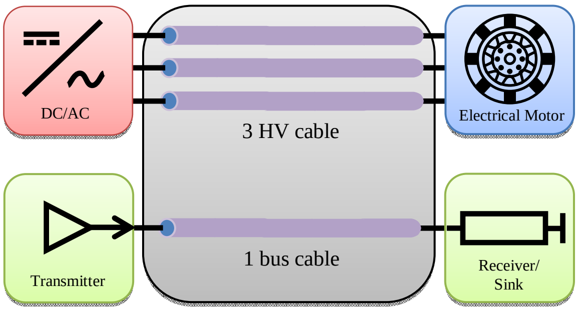

Figure 1. Scheme of the involved components

B. Inverse Modified Nodal Analysis (IMNA)

In this section a new inverse method to specify the shape of disturbance pulses or circuit parameters based on a given nodal voltage (sink or victim voltage) is described. This method is based on the modified nodal analysis (MNA) which is described first. Subsequently the extensions needed for the inverse Modified Nodal Analysis (IMNA) are outlined.

The MNA is a method to analyze the nodal voltages and branch currents in an electric circuit. This method is frequently used in circuit simulation programs [4]-[7]. To analyze an electric circuit in the time domain, the following equation is used:

$$\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{G}\mathbf{x}(t)=\mathbf{w}(t) \tag{1}$$

The vector $\mathbf{x}(t)$ contains the unknown voltages and special currents. The vector $\mathbf{w}(t)$ includes all known excitations. The matrices **C** and **G** characterize the circuit.

By calculating for example the shape of a disturbance pulse, that does not hit a limit line (nodal voltage shape), several computations of the vector $\mathbf{x}(t)$ with several input vectors $\mathbf{w}(t)$ would be necessary using the standard formulation (MNA). In this method search algorithms are required to find the excitation voltage or current shape. In order to find an excitation signal shape over time for a given nodal voltage an inverse method is better to use and was developed.

1) Calculate disturbance signals in general

It is assumed that the shape of a disturbing pulse is unknown but the sink or victim limit voltage is known. Under the assumption that the source of the disturbance is a voltage source with unknown voltage ($V_{\text{Disturbance}}$) and current ($I_{\text{Disturbance}}$) the vector $\tilde{\mathbf{x}}$ is defined as follows [1]:

$$\tilde{\mathbf{x}}^T=\begin{bmatrix}\mathbf{x} & I_{\text{Disturbance}} & V_{\text{Disturbance}}\end{bmatrix} \tag{2}$$

This leads to a modification of the matrices **C** and **G**. The matrix **C** has to be extended with two rows and columns with zeros because the disturbance source does not influence the derivative. The stamps for the voltage source (orange), the unknown source (red), and the given sink voltage ($V_{\text{Predefined}}$) (blue) are considered in the matrix **G** and the vector **w** [1].

$$\tilde{\mathbf{G}}=\begin{matrix} & l & m & k & M+1 & M+2 \\ l & & & & 1 & \\ m & & \mathbf{G} & & -1 & \\ k & & & & & \\ M+1 & 1 & -1 & & & -1 \\ M+2 & & & 1 & & \end{matrix} \tag{3}$$

$$\tilde{\mathbf{w}}^T=\begin{bmatrix}\mathbf{w} & 0 & V_{\text{Predefined}}\end{bmatrix} \tag{4}$$

The resulting equation system can be solved with known algorithms [7].

2) Considering transmission lines in the inverse method

In order to consider transmission lines combined with predefined signals, the matrices **C** and **G** and the vectors **x** and **w** have to be extended. Basically it must be distinguished between simple transmission lines and multi conductor lines. First simple transmission lines are analyzed.

Based on the transmission line theory, the solution of the telegraph equation in the time domain can be described as [8]:

$$v_1(t)-Z_c i_1(t)=v_2(t-\tau)+Z_c i_2(t-\tau) \tag{5}$$

$$v_2(t)-Z_c i_2(t)=v_1(t-\tau)+Z_c i_1(t-\tau) \tag{6}$$

The voltage and current at the end of the wire ($v_2(t)$ and $i_2(t)$) depends on the voltage and current at the beginning of the wire ($v_1(t)$ and $i_1(t)$) including the delay time τ and the characteristic impedance Z_c of the wire. To consider a transmission line the vector **x** has to be extended with the branch currents of the line:

$$\tilde{\mathbf{x}}^T=\begin{bmatrix}\mathbf{x} & i_1 & i_2\end{bmatrix} \tag{7}$$

In the inverse method it is not possible to include the equations (5) and (6) directly in the matrices **C** and **G**. It is necessary to transform both equations. It is assumed that the predefined signals are given at the end of the wire (index 2). This implies that the sink signal is known at all times and that these values can be used as future values in the matrices. As a result the solution of the telegraph equation (6) has to be rewritten as follows:

$$v_2(t+\tau)-Z_c i_2(t+\tau)-v_1(t)-Z_c i_1(t)=0 \tag{8}$$

This leads to changed vectors *x* and *w* and matrices **C** and **G**. The Matrix **C** is extended with two rows and columns with zeros. In the matrix **G** and the vectors these equations have to be incorporated as follows [1]:

$$\tilde{\mathbf{x}}^T = [v_1(t) \quad v_2(t+\tau) \quad \cdots \quad i_1(t) \quad i_2(t+\tau)] \tag{9}$$

$$\tilde{\mathbf{G}} = \begin{array}{c} \\ a \\ \\ b \\ \tilde{M}+1 \\ \tilde{M}+2 \end{array} \begin{array}{c} \begin{array}{cccc} a & b & \tilde{M}+1 & \tilde{M}+2 \end{array} \\ \left[\begin{array}{cccc} & & 1 & \\ & \mathbf{G} & & \\ & & & 1 \\ 1 & & -Z_C & \\ -1 & 1 & -Z_C & -Z_C \end{array} \right] \end{array} \tag{10}$$

$$\tilde{\mathbf{w}}^T = \left[\mathbf{w} \quad v_2(t-\tau) + Z_C i_2(t-\tau) \quad 0\right] \tag{11}$$

The resulting system of DAE (differential algebraic equations) has to be solved. To consider multi conductor transmission lines the approach has to be modified. Instead of using scalar quantities, vectors have to be used. Based on the transmission line theory the solution of the telegraph equation in the time domain for multi conductor transmission lines can be described as [8]:

$$\mathbf{V_{1m}}(t) - \mathbf{Z_{cm}}\mathbf{I_{1m}}(t) = \left(\mathbf{V_{2m}}(t-\tau_m) - \mathbf{Z_{cm}}\mathbf{I_{2m}}(t-\tau_m)\right) \tag{12}$$

$$\mathbf{V_{2m}}(t) - \mathbf{Z_{cm}}\mathbf{I_{2m}}(t) = \left(\mathbf{V_{1m}}(t-\tau_m) - \mathbf{Z_{cm}}\mathbf{I_{1m}}(t-\tau_m)\right) \tag{13}$$

For the nodal analyses of multi conductor lines it is important to decouple the whole system. This is done with transformation matrices. One transformation matrix for decoupling the voltages ($\mathbf{T_V}$) and one for the currents ($\mathbf{T_I}$) are needed.

$$\mathbf{V} = \mathbf{T_V}\mathbf{V_m} \tag{14}$$

$$\mathbf{I} = \mathbf{T_I}\mathbf{I_m} \tag{15}$$

After the calculation the nodal quantities are:

$$\tilde{\mathbf{x}}^T = [v_1(t) \quad v_2(t+\tau) \quad \cdots \quad i_1(t) \quad i_2(t+\tau)] \tag{16}$$

To get the correct values for the voltages and currents it is necessary to extract the delay time τ in all previously delayed signals. After that the vector **x** is:

$$\tilde{\mathbf{x}}^T = [v_1(t) \quad v_2(t) \quad \cdots \quad i_1(t) \quad i_2(t)] \tag{17}$$

III. Application of the Methods

In this section applications for both methods are shown. As described before, the search method combined with MNA is used to calculate a minimal distance between wires. The inverse method (IMNA) is used to determine a shape of disturbance sources.

1) Determine the minimal distance

To determine the minimal distance the configuration described in Figure 1. is analyzed. As described before, precise models of each component are necessary. One way to combine such different components in a simulation is VHDL-AMS (Very High Speed Integrated Circuit Hardware Description Language – Analog and Mixed Signal). This modeling language is supported by the FlexRay consortium and the German working group VDA FAT AK-30 by developing and providing VHDL-AMS model libraries [9].

The DC/AC inverter drives the electric motor with a pulse width modulated (PWM) signal. Such a configuration can be found in electric vehicles (EV). Here the voltage amplitudes can be high (300 V and more), and the slopes steep. Coupling problems are possible. Cables for high voltages are often shielded. If there are failures in the system, e.g. the contact to ground of the shield of a HV cable is not reliable, significant coupling to bus cables running in parallel can occur [2]. Also unshielded HV cabels can be used in order to reduce the cost and the weight of a vehicle.

Models of the electric motor and the DC/AC inverter from [9] are used here. Instead of a typical EV-DC voltage of around 300 V, 75 V is used here for the calculation because the inverter model is only verified up to this voltage level so far [10].

The multi conductor transmission line model considers electromagnetic coupling between the lines and frequency dependent losses, as the skin effect [11]. This is important for the simulation of pulses with steep slopes containing high frequency parts. For the simulation a 35 mm^2 cross section HV cable is used. The used cross section of the bus cable is a typical value, 0.35 mm^2. Figure 2. shows the configuration used for the simulation. While keeping the distance between the HV cables d_E constant to a minimum of the typical isolation thickness, the distance h_E between the HV cables and the reference plane and thus to the bus cable is varied. Furthermore the parallel length of the cables is varied step by step to find critical coupling. It is also possible to vary the parameters like distance and length automatically and apply advanced search algorithms [12]. Anyway, many computation iterations are needed where the simulation has to be started all over again.

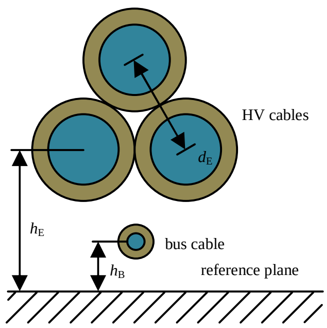

Figure 2. Cross section of the multi conductor line configuration

As an example, a LIN (Local Interconnect Network) bus system with accurate models of LIN transceivers is analyzed.

The simulation results of this network in comparison to the minimal eye diagram of a LIN bus are shown in Figure 3.

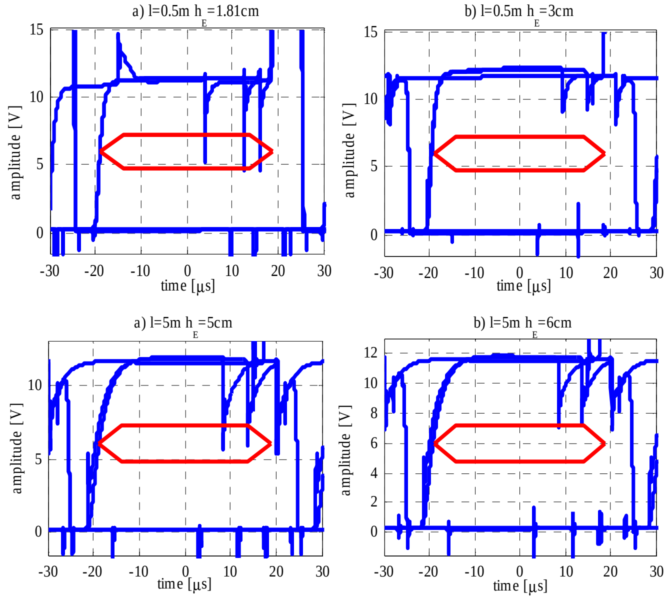

Figure 3. a) broken and b) not effected eye diagrams of the LIN signal

In Figure 3. limit cases where the eye diagram is affected and not affected are shown. After several simulations critical length and distance combinations could be found.

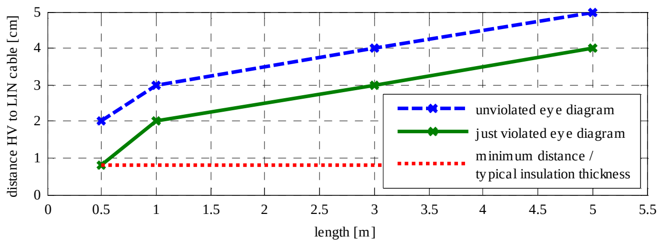

Figure 4. Limits for distances at parallel lengths of HV and LIN cables

In Figure 4. the minimal distances between the LIN bus cable and the HV cable are shown over length. The affected eye diagrams do not necessarily lead to wrong bit detection, because the disturbances are very short and might not be recognized by a typical transceiver. On the other hand these results are no worst case scenarios. The DC voltage is only 75 V. For higher voltages the disturbance will lead to greater minimal distances.

2) IMNA

There are many different applications for an inverse circuit analysis. In this paper three examples are presented to verify the method and to demonstrate the applicability. The first configuration consists of a single wire disturbed by capacitive coupling. In the second example cable crosstalk is analyzed. The last example deals with a simple cable to antenna coupling configuration to analyze electromagnetic radiation at low frequencies.

As a first example a simple data transmission via a single wire over ground is assumed. The capacitive coupled disturbance source is located at the beginning of the wire and the victim signal at the end. The structure of the network is shown in the following figure. Here it is assumed that the disturbance source should not produce pulses that can be interpreted as communication signals.

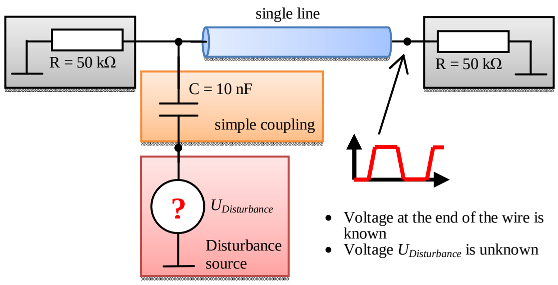

Figure 5. Network: Single Wire

The determined disturbance signal (Figure 6.) was used as a voltage source in the MNA to verify the method.

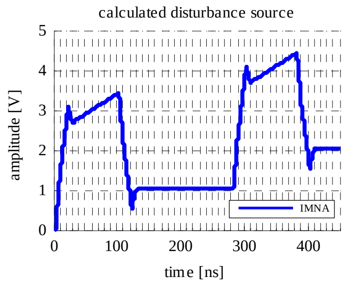

Figure 6. Shape of the disturbance source

In the next figure, the comparison between the simulation results of both methods (IMNA and MNA) is shown.

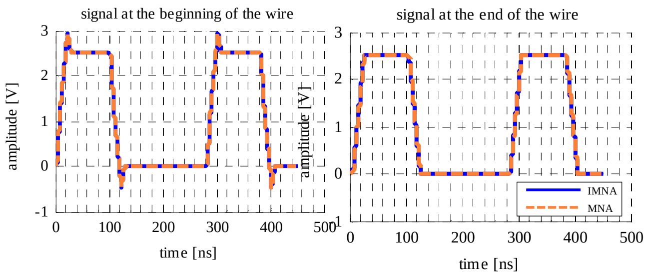

Figure 7. Signals of the network

It is possible to generate the given sink nodal voltage with the calculated disturbance voltage. The comparison with the MNA yields no difference.

The second configuration is a system consisting of two wires with different diameters. It is shown in Figure 8. For the receiving node a typical simple equivalent LIN circuit consisting of a resistor and a capacitor with the values of 30 kΩ and 27 pF is used. The LIN transmitter is modeled as a voltage source with a source resistor of 1 kΩ [13]. The distance between the two wires is 2 cm. A critical signal like the eye diagram is given as sink at the receiver node (Figure 10.). The shape of the source voltage at the beginning of the HV cable has to be determined. This can be done directly with the inverse method.

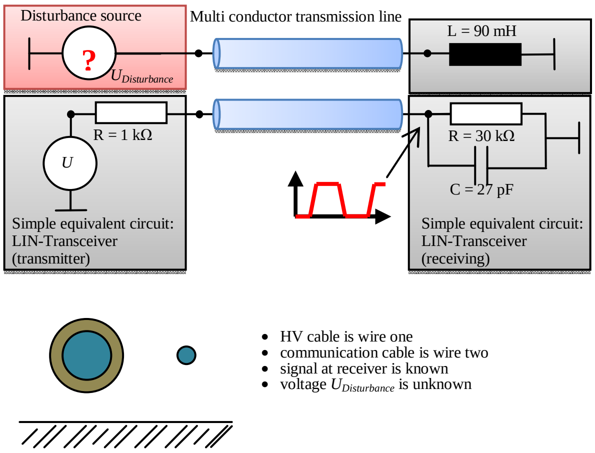

Figure 8. HV cable and LIN communication cable

The inverse method determines the shape of the source that is shown in Figure 9. :

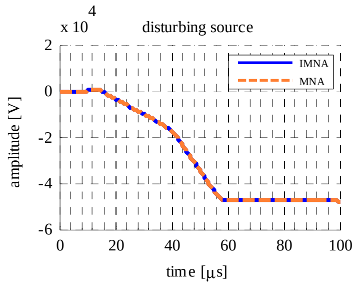

Figure 9. Shape of the disturbance source

To check the accuracy of this method the source is used as input in the MNA to compare the signals at the receiver node.

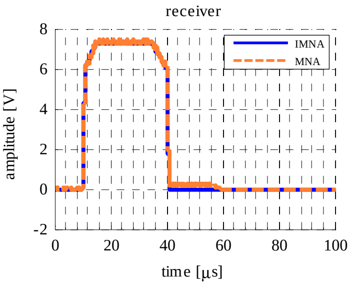

Figure 10. Compare signal at the receiver

The comparison of the results shows that the inverse method is working accurately. By increasing the distance between the wires the amplitude of the disturbance signal is rising but the rise time is nearly the same. As a last application example the field coupling to an antenna is analyzed in the low frequency range. Also here an automotive configuration is taken as an example.

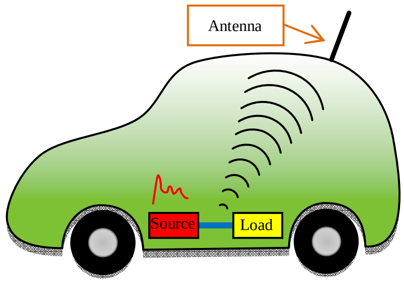

Figure 11. Cable to antenna coupling in vehicle

In the CISPR 25 standard [14] no limit for radiation is given below 150 kHz (Class 5). With the inverse method it is possible to calculate directly a disturbance signal that will emulate the threshold line from CISPR 25 for antenna measurements, but does not exceed it. The following disturbance spectrum is possible.

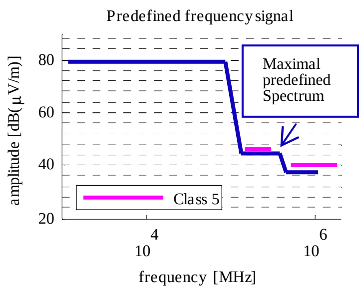

Figure 12. Antenna signal amplitude in frequency domain

Here it is assumed that the amplitude up to 150 kHz is 80 dB (µV). Above that level the amplitude is 45 dB (µV) and for frequencies which are higher than 530 kHz the amplitude is 38 dB (µV). With the inverse Fourier transformation it is possible to calculate a time signal from the given spectrum as shown in Figure 13. The Phase is assumed to be zero.

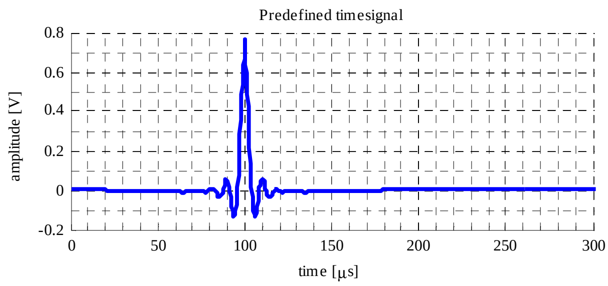

Figure 13. Antenna time signal

This time signal is used as the sink signal at the antenna port. The equivalent circuit for the configuration for analysis is shown in Figure 14. Due to the low frequencies an electric short antenna and only capacitive coupling can be assumed.

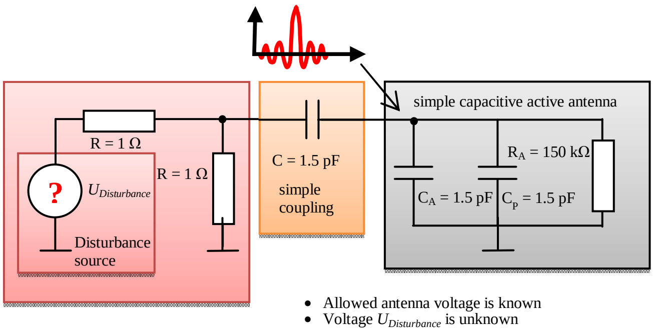

Figure 14. Equivalent ciruit for cable antenna coupling in low frequncy range

By using the IMNA the disturbance voltage is calculated (Figure 15.).

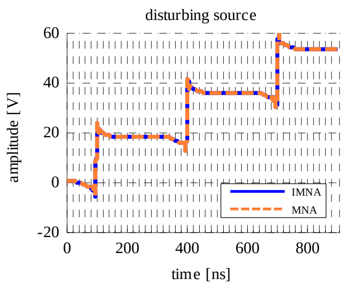

Figure 15. Disturbance source voltage

This disturbance source voltage is used as a voltage source in the MNA. The comparison of the simulation results of both methods is shown in Figure 16.

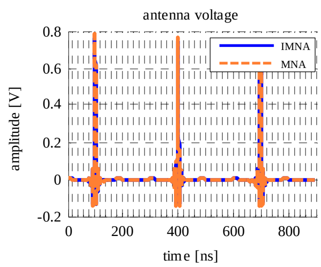

Figure 16. Antenna voltage

Here it could also be shown that IMNA gives the correct source voltage.

IV. Discussion

Two methods for computation of critical coupling configurations are shown. The benefit of the direct network analysis and the search methods is the possibility to use advanced network simulation programs and available model libraries. But it is necessary to repeat the simulation several times and this may take a long time. For the inverse method only one simulation run is necessary. That is why the simulation time is much shorter. The algorithm for solving a network inversely is new and not yet supported by commercial simulation programs. Only simple configurations can be considered today.

V. Summary and Outlook

Identifying critical coupling parameters by simulation can be seen as a standard problem in EMC. The conventional approach is using simulations and searching algorithms. This method can be used with any kind of simulation program but can be very slow. A new direct inverse method based on Modified Nodal Analysis is presented. This method can give directly with one simulation run critical voltage shapes, when the permitted noise margin is given. Currently only a basic implementation of this method is available. In the future the inverse method will be extended to calculate arbitrary circuit configurations.

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