Uncertainties of immunity measurements

DTI-NMSPU project R2.2b1

Annex A Description of the circuit model (conducted immunity)

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Annex A

Description of the circuit model

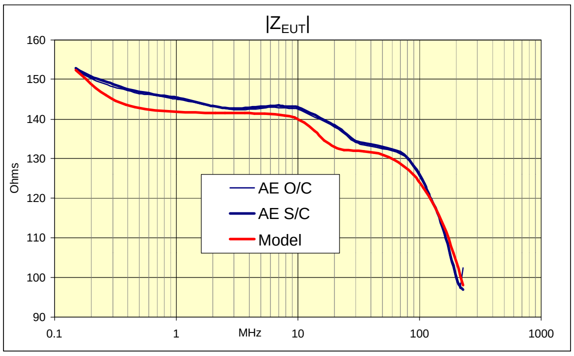
This annex gives detailed information on the circuit model used for the conducted immunity analysis.

Circuit analysis package

The modelling used Number One Systems' "Analyser for Windows". This allows the gain from one port to another to be calculated in up to 100 steps across any given frequency range. The circuit information is provided from a netlist which details the resistor, inductor, capacitor, transmission line and transformer components. The netlist is derived from circuit diagrams as shown below (Figure 7 - Figure 9). Although it is also capable of using frequency-dependent files which could be used to describe ferrite components, the extra effort needed to characterise and validate the data for such components was not felt to be justified.

Development and validation of models

The circuit models for each transducer and for the overall equivalent circuit of the measurement were developed separately and the transducer models were verified by comparing their calculated impedance profiles to calibration data of actual transducers. An example for the CDN is shown in Figure 1 and for the EM-clamp in Figure 2.



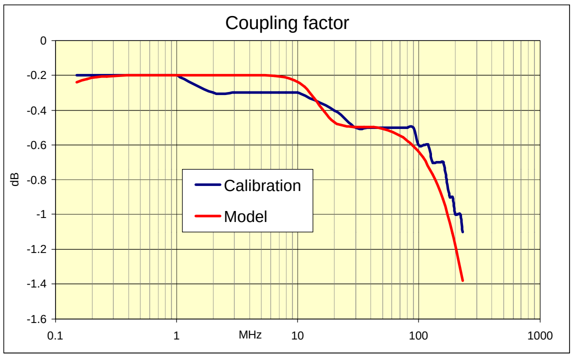


Figure 1 CDN-M1 actual calibration data and model result: impedance and transducer factor

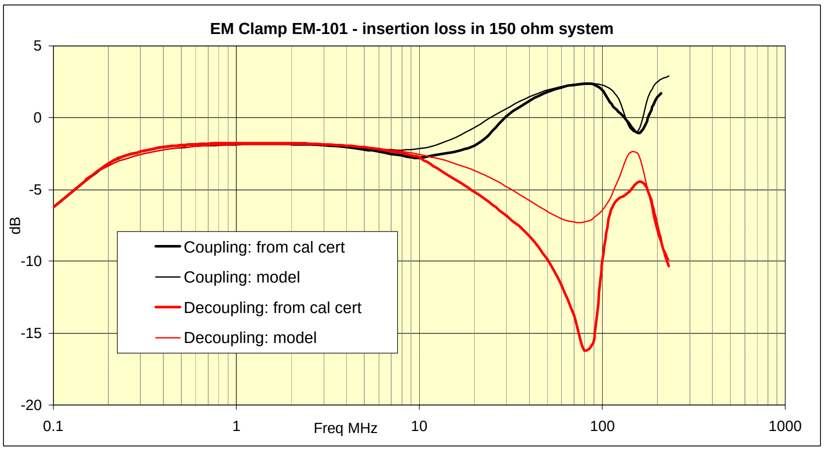


Figure 2 Example calibration gain for EM-clamp: forward (coupling) and reverse (decoupling)

Each transducer model was then used in the IEC 61000-4-6 150 ohm calibration circuit to determine the input-to-calibration-point gain over the required frequency range $G(f)_{CAL}$.

For each transducer and EUT impedance, a reference model was then developed from the appropriate components and this was used to generate the raw gain data $G(f)_{EUT}$ from the input to the point of measurement , coupled through the BNC output port and coax cable to the AE port of the CDN-S1. Various impedance values were changed as shown on the circuit diagrams to simulate the variations in conditions that were the basic input for the analysis.

The ratio $\frac{G(f)_{CAL}}{G(f)_{EUT}}$ then gives the output level in dBV measured across the 3Ω resistor in the EUT that would be achieved for a stress level applied of 1V.

This quantity is used as the primary output value in all subsequent reporting as it is directly equivalent to the value derived in the measurement programme described in Annex B, and takes full account of the pre-calibration method of IEC 61000-4-6 which in theory removes the variations due to different transducers.

Transmission line equivalence of cable layout

The cables between the EUT and its coupling devices, and for the clamps, between the clamp and the AE, can be represented in common mode by a transmission line whose ground terminal is the test setup ground plane. The length of the transmission line is equal to the length of the cable between its connections – or to the edge of the clamp – and the Z_0 is determined by the cable's effective diameter and its height above the ground plane. For this exercise, the effective diameter was assumed to be between 4mm and 12mm as this is likely to cover the majority of tested cables. This then gives a range of calculated Z_0 as shown in Table 1.

$$Z_0 \quad = \quad 60 \ln\{2h/D + \sqrt{((2h/D)^2 - 1)}\}$$

Diameter mm	4		8		12		6
Height mm	30	50	30	50	30	50	7
Z_0 ohms	204.0	234.7	162.2	193.0	137.5	168.6	89.5

Table 1 Range of Z_0

For the modelling, the Z_0 is taken to lie within the range 140 – 220Ω and these were the extremes, together with the lengths of 10cm and 30cm, used to give the results showing cable variations in the main report.

The overall equivalent circuits

The conceptual equivalent circuit is shown in Figure 3. The transducer has a port to the EUT and a port to the AE, each of which is connected through a transmission line representing the cable section. The AE is represented by its common mode impedance Z_{AE}. The EUT is represented by its port impedance Z_{IN} feeding into a transmission line which represents the EUT structure. At a height of 10cm above the ground plane, and for an EUT dimension of 28 x 43 cm, this approximates to a 70Ω line of length 43cm, according to the stripline equation:

$$Z_0 \quad = \quad 377 \cdot 1/\{w/h + 1.393 + 0.667 \cdot \ln((w/h) + 1.444)\}$$

These values are used throughout the modelling. The case of the EUT is connected at the far end via another length of cable, represented as a further transmission line, to the second CDN (S1) which is used to pick off the measured RF at the input. Both this CDN and the cable have a common mode impedance of 150Ω.

It should be appreciated that this coax cable does two things; it transports the measurand, and it provides a defined 150 ohm common mode impedance for the EUT, as is required in the standard. Figure 3 is only an outline of the *injection* equivalent circuit, not of the measurement also. The measurement circuit is given by the circuit models Figs 7-9 and the circuit of the dummy EUT in Annex B. In the circuit models, because the output voltage must be ground-referred, it is taken via an ideal transformer and thence to the 47 ohm matching resistor to the output measuring point. Ignoring the loss in the coax cable, this is equivalent to the actual circuit where the 47 ohm matching resistor is connected directly to the 3.3 ohm shunt resistor across which the output voltage is developed.

CDN

The CDN equivalent circuit (Figure 4) is based on the principal impedance determining components L1, R_S + 100R, C2 and C3 as are defined in the standard. These are modified by stray reactances and subsidiary components which appear in the real unit; the values for these are derived by mimicking the measured calibration results in the model. The tuned circuit components L_A and C_A represent the series inductance of the bond to the ground plane, and the capacitance of the CDN enclosure to the ground plane. For a good bond, L_A is very low; a bad bond is represented by a 0.1µH inductance which is roughly equivalent to a 12cm length of wire.

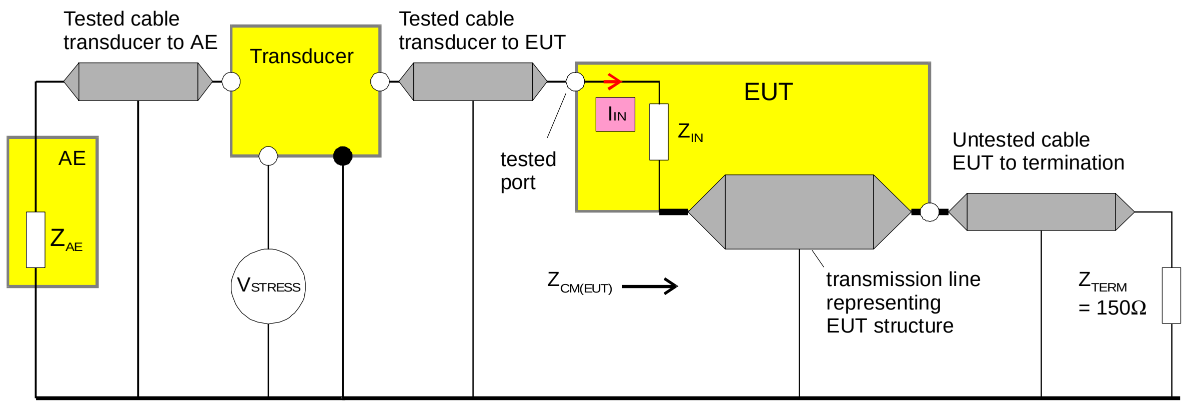


Figure 3 Outline equivalent circuit of the injection process

Current injection probe

The current injection probe (Figure 5) is represented by a transformer whose 1-turn secondary is part of the cable under test. The number of primary turns and self-inductance are taken from the probe data. Stray capacitance between the probe case and the cable is represented by C1a,b and the self-resonance of the probe, taken from the calibration curve, is given by C2. When the inductance of the strap bonding the probe case to the ground is significant, the common mode impedance of the cable between the generator and the probe must be included in the model; this is given by a transmission line, whose values represent a 1m length of 6mm dia cable 7mm above the ground plane (see Table 1). This value is not controlled in the standard but is felt to be representative of typical setups.

EM-Clamp

The EM-clamp is more complicated than either the CDN or current probe. The equivalent circuit (Figure 6) is in the first instance derived from the physical construction of the clamp: this is made up of two groups of ferrites arranged in series together with a capacitive coupling electrode running the length of the device. The low frequency ferrites around the CUT (cable under test) are represented by transformers T1, T2 and T3, and the high frequency ferrites by T4 and T5. The capacitive electrode coupling to the CUT are represented by transmission lines TL1-6. The transformers are effectively lumped elements separated by the transmission lines to give a quasi-distributed effect. L2 and R2 are the elements given by the standard specification Z2. The impedance of the transmission lines are initially set to represent an approximately correct coupling capacitance to the cable based on the constructional geometry, while the transformer parameters are set by the intrinsic properties of the ferrites, whose frequency dependencies are ignored. L_A and C_A are governed by the grounding impedances as discussed above for the CDN.

The modelled values (including the loss resistors) are refined by an iterative comparison of the predicted insertion loss in the forward and reverse directions against the calibration results for the actual clamp. These values eventually provided the curves shown in Figure 2. Although this does not exactly replicate the calibration, particularly with respect to the maximum directivity from 50 to 100MHz, it is close enough to be useable. Undoubtedly a more accurate simulation of the clamp would be possible but whether it would substantially improve the accuracy and relevance of these results is doubtful.

Final equivalent circuits

The actual circuit models used are shown in Figure 7, Figure 8 and Figure 9. These drawings also show the values used for the dummy EUT Z_{IN}.

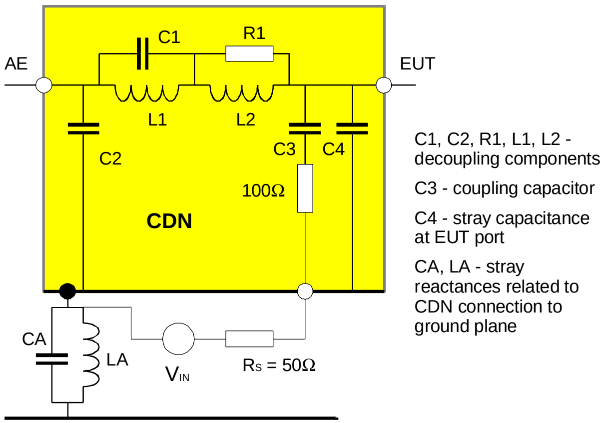


Figure 4 Circuit model for CDN

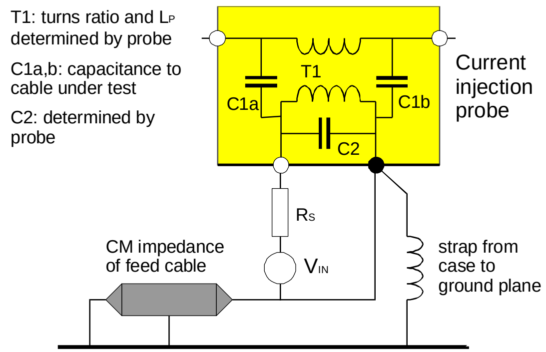


Figure 5 Circuit model for current injection probe

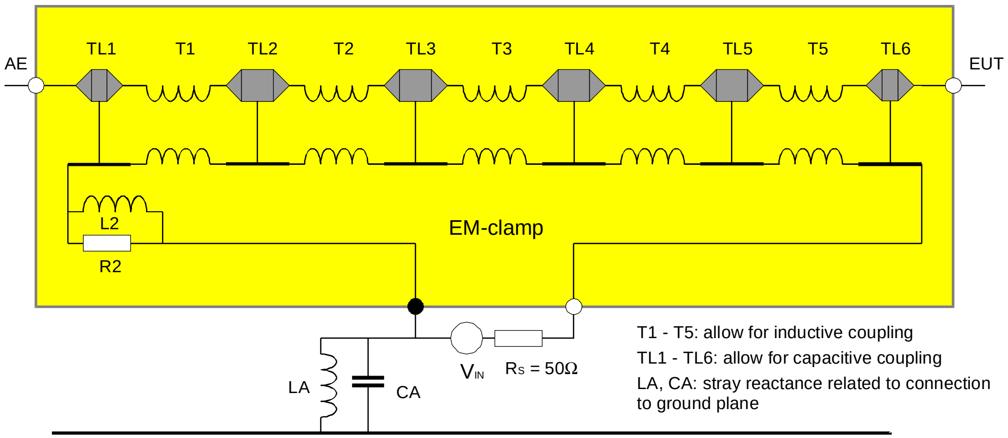
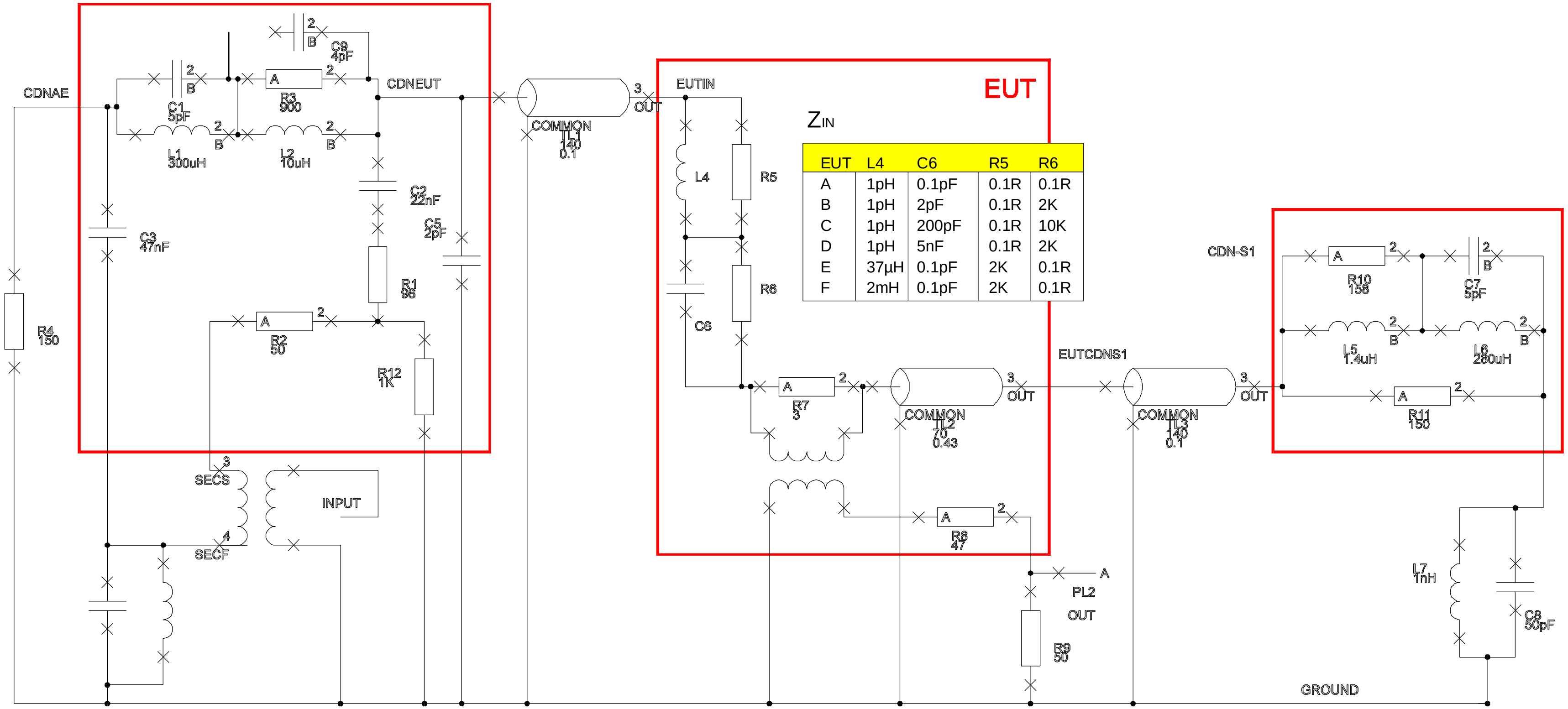
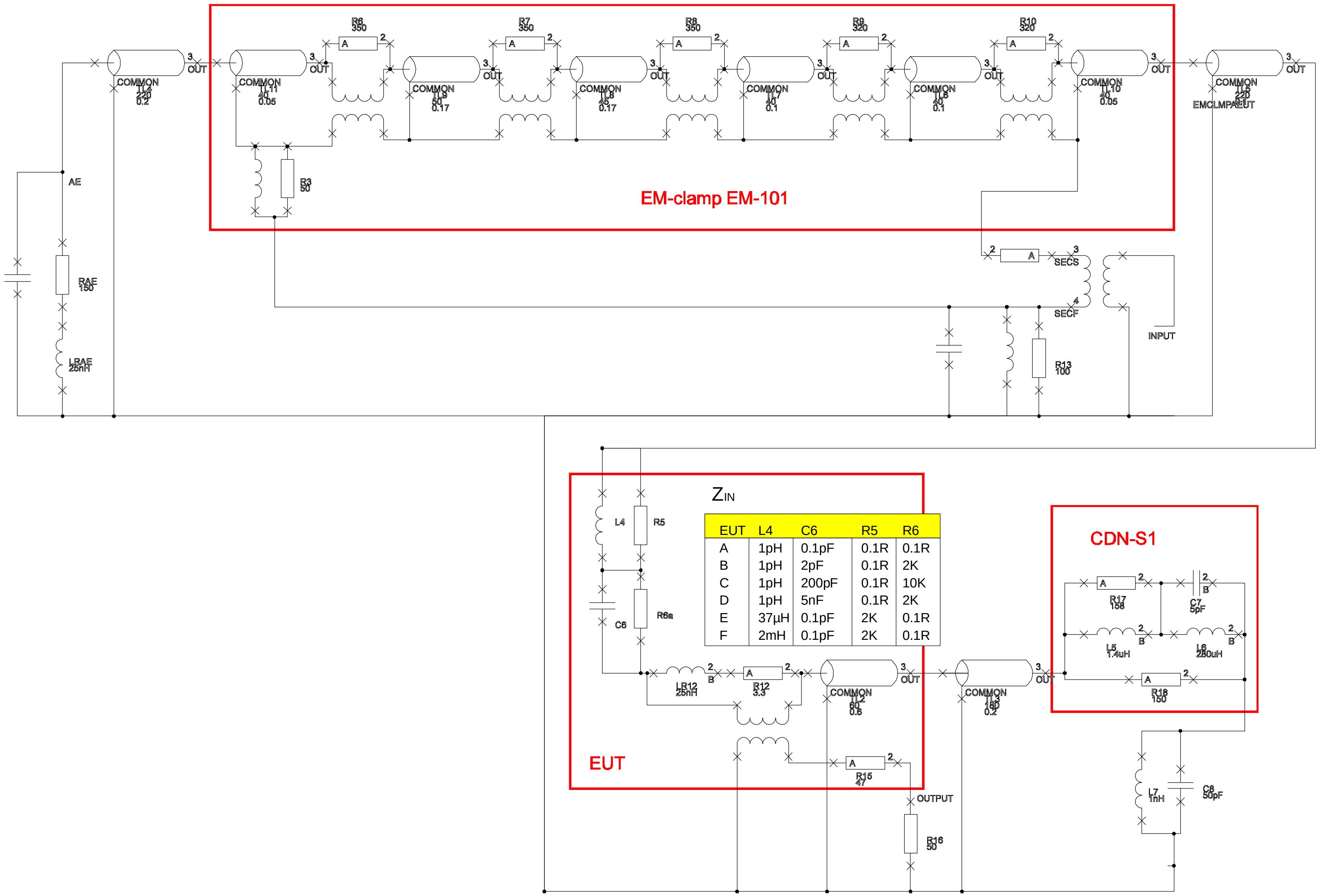


Figure 6 Circuit model for EM-clamp



EUT	L4	C6	R5	R6
A	1pH	0.1pF	0.1R	0.1R
B	1pH	2pF	0.1R	2K
C	1pH	200pF	0.1R	10K
D	1pH	5nF	0.1R	2K
E	37µH	0.1pF	2K	0.1R
F	2mH	0.1pF	2K	0.1R

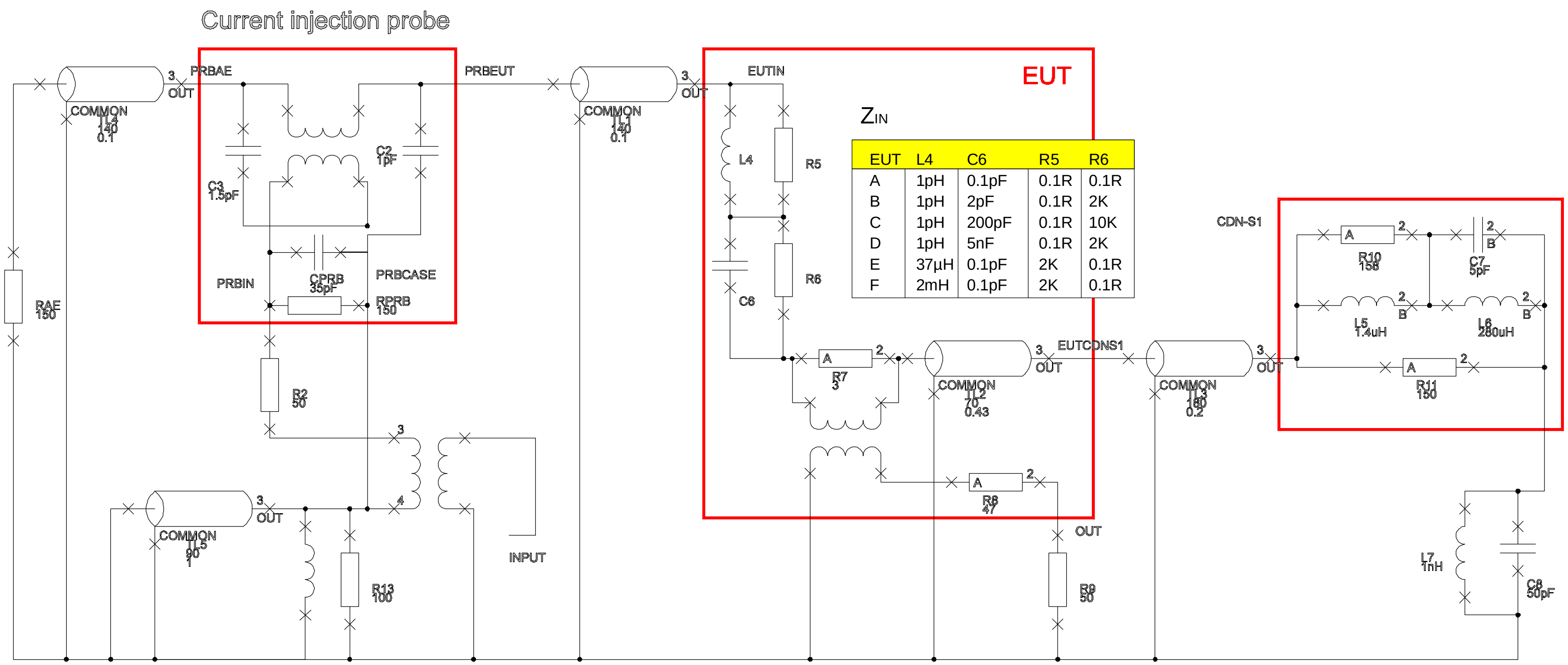
Figure 7 Overall circuit model for CDN transducer, EUT, AE and second CDN



Z_{IN}

EUT	L4	C6	R5	R6
A	1pH	0.1pF	0.1R	0.1R
B	1pH	2pF	0.1R	2K
C	1pH	200pF	0.1R	10K
D	1pH	5nF	0.1R	2K
E	37µH	0.1pF	2K	0.1R
F	2mH	0.1pF	2K	0.1R

Figure 8 Overall circuit model for EM-clamp transducer, EUT, AE and second CDN



EUT	L4	C6	R5	R6
A	1pH	0.1pF	0.1R	0.1R
B	1pH	2pF	0.1R	2K
C	1pH	200pF	0.1R	10K
D	1pH	5nF	0.1R	2K
E	37μH	0.1pF	2K	0.1R
F	2mH	0.1pF	2K	0.1R

Figure 9 Overall circuit model for current injection probe transducer, EUT, AE and second CDN