Electromagnetic Field and Impedances of High Current Busducts

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Abstract—**Paper presents results of numerical computation of electrical parameters of the flat and symmetrical three-phase high current busducts. Into account the skin and proximity effect were taken.**

Keywords-high current busduct; tubular busbar; electromagnetic field; eddy currents; impadance

I. INTRODUCTION

Following the development of thermal and hydroelectric power stations, at the beginning of the 30s, high current transmission lines with screened busducts connecting big generators with unit transformers began to be installed. The contemporary solutions consist of transmission lines isolated with air at atmospheric pressure, with duty-rated voltage values reaching up to 36 kV and duty-rated current values reaching up to: 10 kA for hydroelectric power plants, 20 kA for thermal and nuclear plants whose duty-rated power values reach up to 900 MW, 31,5 kA for nuclear plants with power value of 1300 MW [1-3].

Power industry has been using high current transmission lines with gas insulated phases since the 70s. The gas most commonly used is SF_6 (sulphur hexafluoride) whose pressure values range from 0,29 to 0,51 MPa (at $20^{o}C$) . Recently SF_6 has been replaced with a mixture consisting in 95% of N_2 and in 5% of SF_6 of 1,3 MPa pressure, corresponding to 0,4 MPa pressure in the case of pure SF_6 [1-6].

Nowadays such transmission lines are built for voltage values ranging from 72 to 1200 kV but most often for voltage values ranging from 110 to 750 kV, duty-rated current values ranging from 1 to 12 kA and duty-rated power values ranging from 200 to 4000 MV·A. The case when the application of gas insulated high current transmission lines brings the most advantages is when they are used for voltages higher than 245 kV and transmission of power values ranging from 2000 to 4000 MV·A. [1-6]

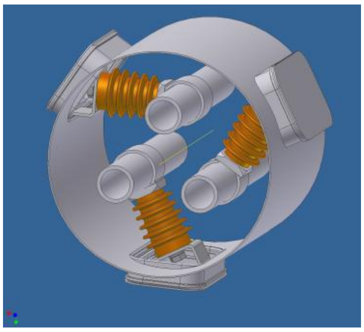


Figure 1. Three-pole high current busduct [7]

Figure 2. Double-circuit GIL in Częstochowa Steelworks

Losses in power transmission in a 420 kV GIL with 2000 MVA power are much lower than for an equivalent overhead or cable line (Fig. 3 and table 1).

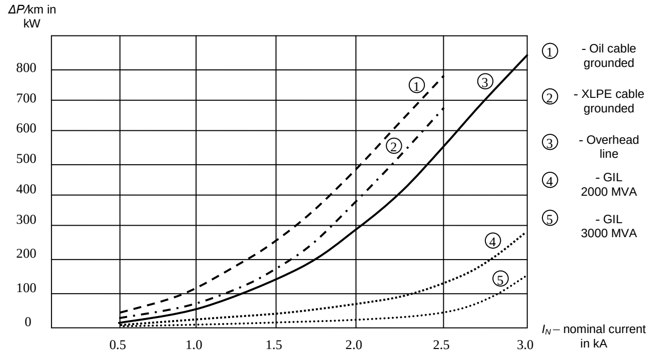


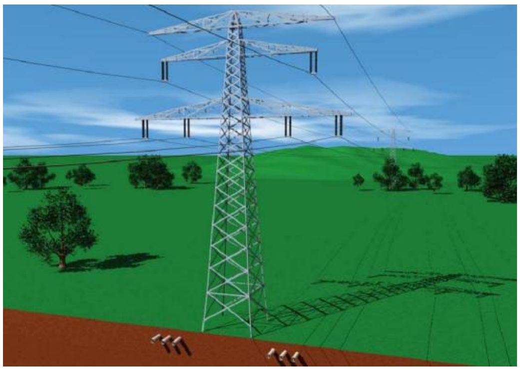
Figure 3. Transmission losses of different 420 kV systems [8]

TABLE I. COST DIFFERENCES OF TRANSMISSION LOSSES OF OHL AND GIL [8]

	OHL	GIL
Transmission power	2000 MW	2000 MW
Losses per system-meter	820 W/m	180 W/m
Losses of 100 system-km	82 MW	18 MW
Difference between GIL and OHL	**64 MW**	
Difference in the cost of losses per year	**27 520 000 €**	
Investment GIL (100 km)	300 000 000 €	

Due to financial and environmental-landscape protection requirements as well as weather conditions (hurricanes, thunderbolts) it is believed that GILs will replace before all overhead lines and they will be laid along highways or in traffic tunnels and used in particular to supply huge cities or industrial zones with power (Fig. 4).

a)



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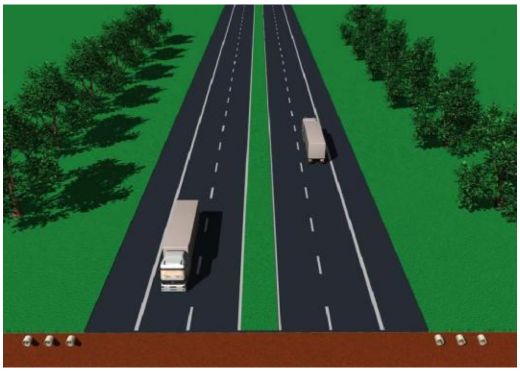

c)

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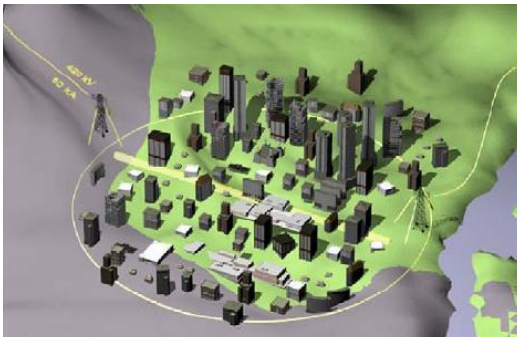


Figure 4. Future applications of GIL [6]:a) overhead transmission line replaced by GIL (the poles are removed), b) GIL installed along a highway, c) rail and road tunnels, d) power supply of metropolitan areas

II. FLAT AND SYMMETRICAL HIGH CURRENT BUSDUCTS

Isolated phase (single-pole) high current busducts are built for high and very high voltages. Each phase is placed in a separate enclosure (IPGIL - **I**solated **P**hase **G**as **I**nsulated **L**ine) - Fig. 5.

The phase conductor is usually a tubular or molded conductor made of aluminum or aluminum or copper alloy. The enclosures are made of aluminum alloys, more rarely of non-magnetic steel. If the transmission line is laid in the ground an external concentric steel cover is additionally installed.

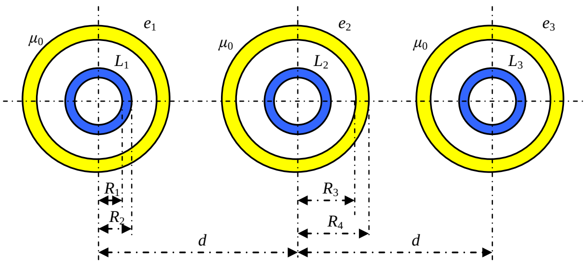


Figure 5. Flat three-phase high current busduct

Electromotive forces produced by the alternating magnetic field of currents in phase conductors are induced in the enclosures of high current transmission lines. If these enclosures are interconnected or grounded the so-called return currents will appear in them. The values of these currents depend on the way the enclosures are interconnected, on the way they are grounded and on electrical parameters of a sheathed high current busduct, i.e. self impedances of phase conductors and enclosures and mutual impedances between conductors and enclosures.

The enclosures of high current busducts are continuous, interconnected and grounded at their endings or also at intermediary points.

Currents $\underline{I}_1$, $\underline{I}_2$ and $\underline{I}_3$ in phase conductors induce electromotive forces in the enclosures. In the case of enclosures being interconnected and grounded return currents $\underline{I}_{e1}$, $\underline{I}_{e2}$ and $\underline{I}_{e3}$ will flow in them, which will also induce electromotive forces in the enclosures. So the values of these return currents depend on the values of currents $\underline{I}_1$, $\underline{I}_2$ and $\underline{I}_3$ and on electrical parameters of the transmission line (and in particular on the mutual inductance between the conductors and the enclosures) and they can be determined from the equivalent diagram shown in figure 6.

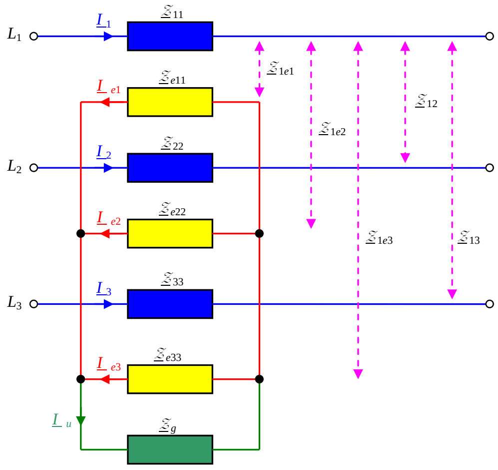


Figure 6. Equivalent diagram of a flat single-pole sheathed high current busduct with interconnected and grounded enclosures (in the figure we omit the mutual impedances referring to phases L_2 and L_3); $\underline{Z}_g$ - impedances of the grounding

Due to the fact that phase conductors enclosures can be interconnected directly or through the grounding the currents in the enclosures are not equal to the relevant currents in phase conductors. Hence we can not use the formulas defining the total impedances of a system of phase conductor-enclosure, but self impedances of these components of the high current busduct as well as mutual impedances between them and between neighboring phase conductors and enclosures have to be determined separately.

Cross-sections of conductors and enclosures of gas insulated high current transmission lines are usually large and when determining their electrical parameters, even for industrial frequency, one should take into account skin effect, which influences considerably their self and mutual impedances.

A considerable influence is also exerted by the induction of eddy currents in the enclosures by the magnetic field of the current in the sheathed conductor (internal proximity effect) – Fig. 7 and of currents in the neighboring enclosures and phase conductors (external proximity effect) – Fig. 8.

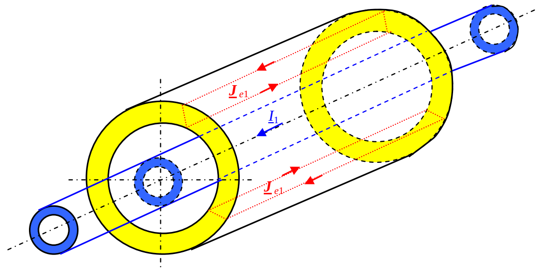


Figure 7. Eddy currents induced in the screen by the magnetic field of the own current of the phase conductor

In practice, a GIL enclosure is a screen which is closed to the magnetic field outside it. It means that the magnetic field in the phase conductor under consideration induces eddy currents only in its own enclosure and in the enclosures of neighboring phases.

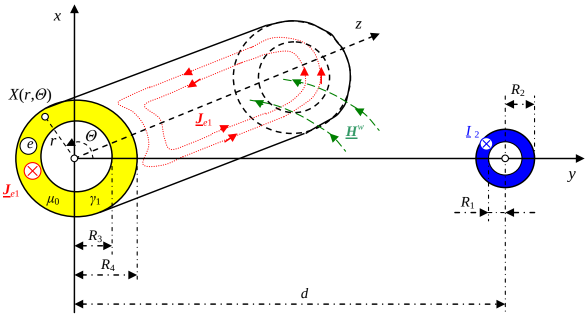


Figure 8. Eddy currents induced in the screen by the magnetic field of the neighboring phase conductor

Thus the self impedance of the phase conductor [3]

$$\underline{Z}_{ii} = \underline{Z}_{ii}^{(1)} + \underline{Z}_{ii}^{(2)} + \underline{Z}_{ii}^{(3)} + \underline{Z}_{ii}^{(4)} \tag{1}$$

where $\underline{Z}_{ii}^{(1)}$ is the impedance of the conductor with regard to skin effect, $\underline{Z}_{ii}^{(2)}$ is the additional impedance with regard to eddy currents induction in its own screen (internal proximity effect) and additional impedances $\underline{Z}_{ii}^{(3)}$ and $\underline{Z}_{ii}^{(4)}$ take into account the induction of eddy currents in the neighboring enclosures by the magnetic field of the phase conductor under consideration (external proximity effect).

Self impedance of the enclosure will be determined in a similar way as for phase conductors but internal proximity effect (enclosure-phase conductor) does not occur for the enclosure, i.e. we do not have impedance $\underline{Z}_{ejj}^{(2)}$, so the self impedance of the enclosure is given as the formula [3]

$$\underline{Z}_{ejj} = \underline{Z}_{ejj}^{(1)} + \underline{Z}_{ejj}^{(3)} + \underline{Z}_{ejj}^{(4)} \tag{2}$$

where $\underline{Z}_{ejj}^{(1)}$ is the impedance of the enclosure with regard to skin effect and additional impedances $\underline{Z}_{ejj}^{(3)}$ and $\underline{Z}_{ejj}^{(4)}$ take into account the induction of eddy currents in the neighboring enclosures by the magnetic field of the current of the enclosure under consideration.

For medium voltages sheathed three-pole high current busducts (Eng. TPGIL - **Th**ree **P**oles **G**as **I**nsulated **L**ine) are built, in which phase conductors are placed in a common enclosure - Fig. 9.

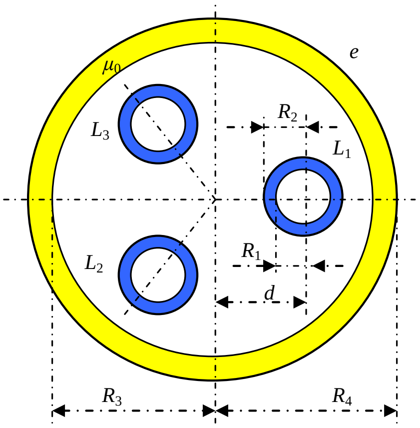


Figure 9. Symmetrical screened three-phase high current busduct

The enclosure of such a high current busduct is continuous and usually grounded at its endings. Then, in the enclosure return current $\underline{I}_e$ will appear, which can be determined from the equivalent diagram of the line shown in figure 10.

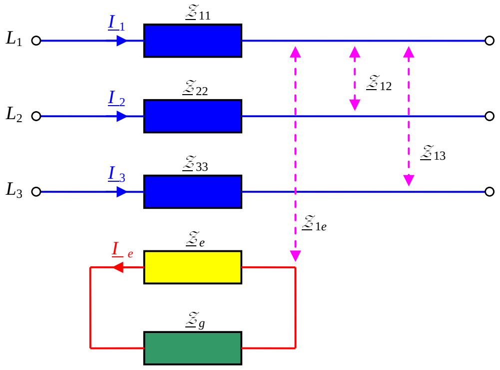


Figure 10. Equivalent diagram of a three-pole sheathed high current busduct with the enclosure grounded at its endings (in the figure we omit the mutual impedances of the phases L_2 and L_3)

The value of return current $\underline{I}_e$ in the screen depends on mutual impedances $\underline{Z}_{ie}$ between phase conductors and the screen and on self impedance $\underline{Z}_e$ of the screen with regard to skin effect and the impedance of the grounding $\underline{Z}_u$.

Self impedances of phase conductors are defined by formula (1), while additional impedances $\underline{Z}_{ii}^{(3)}$ and $\underline{Z}_{ii}^{(4)}$ in the case of this line take into account eddy currents induction in the neighboring phase conductors by the magnetic field of the current of phase conductor under consideration. The magnetic field of current $\underline{I}_e$ in the enclosure does not induce eddy currents in phase conductors, so the impedance of the screen $\underline{Z}_e$ is its self impedance with regard to skin effect.

Due to the fact that cross-sections of conductors and enclosures of gas insulated high current transmission lines (GIL) are usually large, when determining self and mutual impedances of the line, even for industrial frequency, one should take into account skin and proximity effects.

III. NUMERICAL CALCULATIONS

Starting from the three-dimensional Fredholm's equation of second kind with a slightly singular kernel, impedances of a flat and symmetrical high current busduct were calculated. Detailed calculations of electrical parameters of high current busducts are presented in [3]. Results of these calculations contain table 2 and 3.

Using the Helmholz's and Laplace's equation for the The vector magnetic potential the distribution of electromagnetic field in flat and symmetrical high current busducts were determined. Detailed calculations of electromagnetic field are presented in [3].

The distribution of the module of density of current induced in the screen by the screened symmetrical three-phase line according to angle Θ for the constant value of λ, β, ξ and α is shown in figure 11 ($\beta = \frac{R_3}{R_4}$ $(0 \le \beta \le 1)$, $\alpha = \frac{R_4}{\delta_2}$, $\xi = \frac{r}{R_4}$ $(\beta \le \xi \le 1)$, $\lambda = \frac{d}{R_4}$).

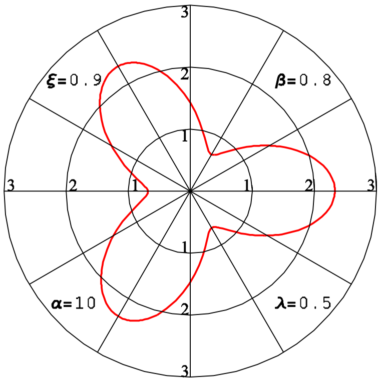
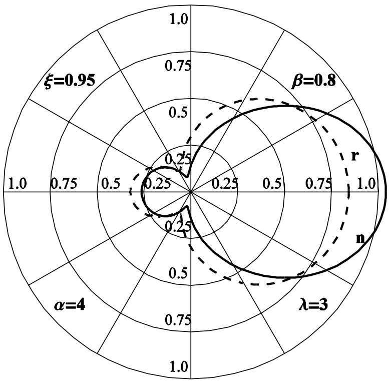


Figure 11. Distribution of the module of relative density of current induced in the screen of a symmetrical high-current transmission line

The distribution of modules of the above densities of currents induced in the screens of a flat three-phase transmission line with isolated phases is shown in figure 12 [3].

a)



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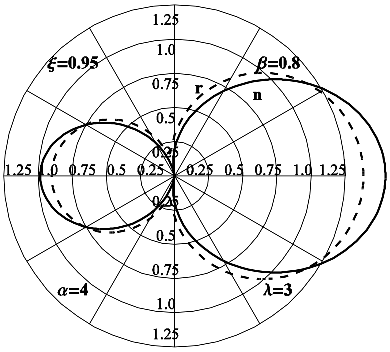

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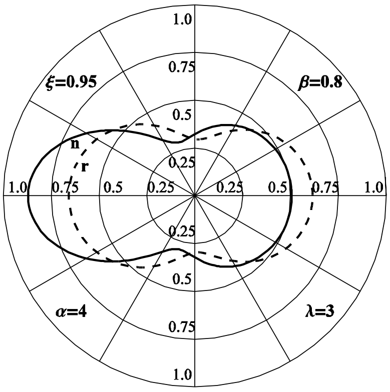


Figure 12. Module of total densities of currents induced in the screens of a flat three-phase single-pole GIL: a) in screen e_1, b) in screen e_2 , c) in screen e_3 ; ***n*** – non-uniform magnetic field, ***r*** – uniform magnetic field

IV. CONCLUSIONS

The enclosures of present-day high-current transmission lines are continuous, short-circuited and grounded at their endings as well as at intermediary points. Then, due to electromotive forces induced by alternating magnetic fields of currents in phase conductors the so-called return currents appear in the enclosures. Their values depend on the way the enclosures are interconnected and on electrical parameters of the screened high current transmission line, i.e. self impedances of phase conductors and enclosures and mutual impedances between them.

Cross-sections of phase conductors and enclosures of high current gas insulated transmission lines (GIL) are usually large and then the determination of their electrical parameters, even for industrial frequencies, should be carried out with regard to skin and proximity effects, which have a considerable influence on their self and mutual impedances. The calculations carried out for high current transmission lines which have been actually built prove that these phenomena should be taken into account in the determination of self impedances of phase conductors. The resistance of these conductors can increase by 80 % of the value of resistance determined for direct current.

Taking into account the so-called reverse reaction of eddy currents induced in the conductors and enclosures of screened high current transmission lines enables, with the simultaneous application of Laplace's and Helmoholtz's equations, the determination of these currents densities by means of analytical formulas expressed by Bessel's functions. These formulas can be applied for phase currents frequency (without shift currents), transverse dimensions, conductivity and geometrical configuration of phase conductors and enclosures of screened high current transmission lines. Next, they can also be used to determine power losses and temperature distributions in phase conductors and enclosures.

TABLE II. RELATIVE VALUES OF RESISTANCES, SELF AND MUTUAL INDUCTANCES OF THE FLAT THREE-PHASE GIL

$R_1 = 29 \cdot 10^{-3}$ m

$R_2 = 45 \cdot 10^{-3}$ m

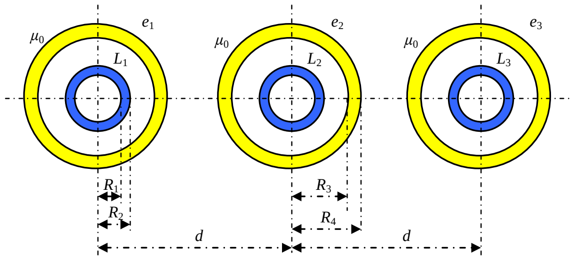
$\gamma_1 = 3{,}7037 \cdot 10^7$ S · m

$R_3 = 174 \cdot 10^{-3}$ m

$R_4 = 180 \cdot 10^{-3}$ m

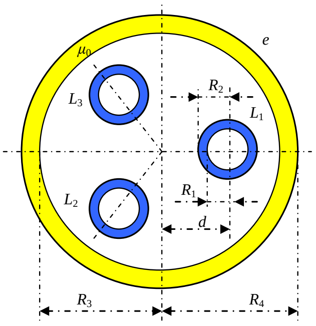
$\gamma_2 = 1{,}8181 \cdot 10^7$ S · m^{-1}

$\boldsymbol{f = 50\,\mathrm{Hz}} \qquad \boldsymbol{d = 3\,R_4}$



l	Extreme phases				Middle phase				Mutual inductances		
	$\frac{\mathcal{R}_{11}}{\mathcal{R}_{11}^{(0)}}$	$\frac{\mathcal{L}_{11}}{\mathcal{L}_{11}^{(0)}}$	$\frac{\mathcal{R}_{e11}}{\mathcal{R}_{e11}^{(0)}}$	$\frac{\mathcal{L}_{e11}}{\mathcal{L}_{e11}^{(0)}}$	$\frac{\mathcal{R}_{22}}{\mathcal{R}_{22}^{(0)}}$	$\frac{\mathcal{L}_{22}}{\mathcal{L}_{22}^{(0)}}$	$\frac{\mathcal{R}_{e22}}{\mathcal{R}_{e22}^{(0)}}$	$\frac{\mathcal{L}_{e22}}{\mathcal{L}_{e22}^{(0)}}$	$\frac{\mathcal{M}}{\mathcal{M}^{(0)}}$	$\mathcal{M}_1$	$\mathcal{M}_2$
m	-	-	-	-	-	-	-	-	-	μH/m	μH/m
1	1,541	0,951	1,280	0,442	1,738	0.923	1,453	0,414	0.999	0,155	0,087
5	1,541	0,966	1,280	0,640	1,738	0,950	1,453	0,622	0.999	0,404	0,286
10	1,541	0,972	1,280	0,688	1,738	0,957	1,453	0,673	0.999	0,533	0,404
50	1,541	0,979	1,280	0,762	1,738	0,967	1,453	0,750	0.999	0,846	0,709
100	1,541	0,981	1,280	0,783	1,738	0,970	1,453	0,773	0.999	0,983	0,846

TABLE III. ELECTRICAL PARAMETERS OF THE THREE-POLE SYMMETRICAL GIL



Busduct EHON-12/2 - Z. I. W. HOLDUCT-Z. H. Ltd. Poland in Pszczyna

$R_1 = 30 \cdot 10^{-3}$ m $\quad R_2 = 40 \cdot 10^{-3}$ m $\quad \gamma_1 = 3{,}48 \cdot 10^7$ S · m^{-1}

$R_3 = 237 \cdot 10^{-3}$ m $\quad R_4 = 240 \cdot 10^{-3}$ m $\quad \gamma_2 = 3{,}48 \cdot 10^7$ S · m^{-1}

$\boldsymbol{f = 50\,\mathrm{Hz}} \qquad \boldsymbol{d = 2{,}5\,R_2}$

l	Phase conductor		Enclosure		Mutual inductances	
	$\frac{\mathcal{R}_{11}}{\mathcal{R}_{11}^{(0)}}$	$\frac{\mathcal{L}_{11}}{\mathcal{L}_{11}^{(0)}}$	$\frac{\mathcal{R}_{e}}{\mathcal{R}_{e}^{(0)}}$	$\frac{\mathcal{L}_{e}}{\mathcal{L}_{e}^{(0)}}$	$\frac{\mathcal{M}}{\mathcal{M}^{(0)}}$	$\mathcal{M}_1$
m	-	-	-	-	-	μH/m
1	1,4096	0,9126	1,0003	0,3754	0,9999	0,3224
5	1,4096	0,9431	1,0003	0,5937	0,9999	0,6180
10	1,4096	0,9506	1,0003	0,6469	0,9999	0,7532
50	1,4096	0,9621	1,0003	0,7292	0,9999	1,0723
100	1,4096	0,9655	1,0003	0,7539	0,9999	1,2106

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