Influence of the external proximity effect on the power losses in flat three phase high current busduct

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In the paper the influence of the external proximity effect on the active and reactive power in flat three phase high current busduct were presented. Calculations were made using the Poynting theorem and Joule-Lenz law.

1. Introduction

Flat high current busduct with tubular conductors are applied mostly as an unsheathed in switching station, low and high voltages, and sheathed as a connection of big generators and transformers, and also in power transmission in long distance for high value of nominal currents – Fig. 1 and Fig. 2 [1-9].

The design of the busducts used for high currents and voltages causes a necessity of precise describing of electromagnetic, dynamic and thermal effects. Knowledge of the relations between electrodynamics and constructional parameters is necessary in the optimization construction process of the high current busducts [1, 2].

Information about distribution electromagnetic field and power losses is a base into analysis of electrodynamics and thermal effects in the high current busducts. Determination of the power losses into high current busducts enables the calculation of temperature of these devices, which is a basic constructional parameter [1, 2].

Fig. 1. Power station [10]

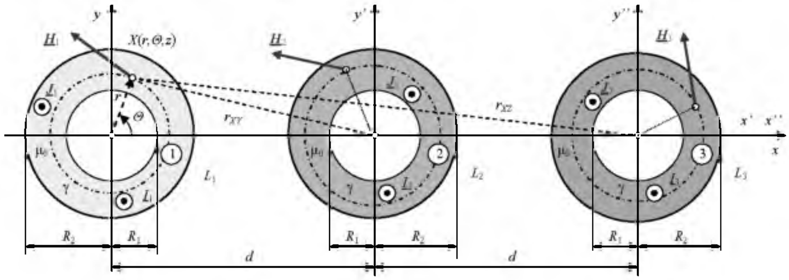


Fig. 2. Flat three phase high current busduct

Power losses depend on value of currents, but for the large cross-sectional dimensions of the phase conductor, even for industrial frequency, skin and external proximity effect (Fig. 3) should be taken into account [5-9].

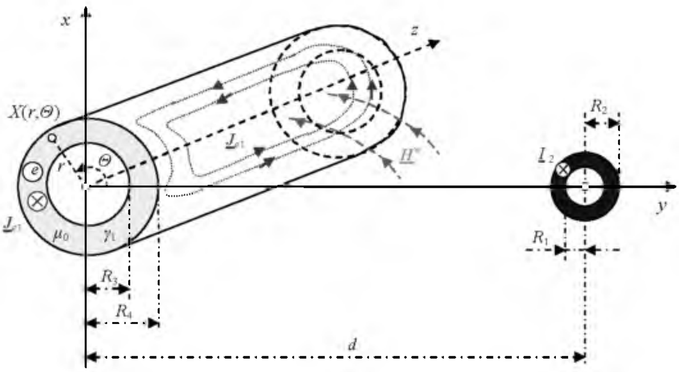


Fig. 3. Eddy currents induced in the screen by the magnetic field of the neighboring phase conductor

2. Electromagnetic field in flat three phase high current busduct

Let us consider the electromagnetic field in flat three phase high current busduct presented in the Fig. 2.

Total density current in the first conductor [5, 7]:

$$\underline{\boldsymbol{J}}_1(r,\Theta) = \underline{\boldsymbol{J}}_{11}(r) + \underline{\boldsymbol{J}}_{12}(r,\Theta) + \underline{\boldsymbol{J}}_{13}(r,\Theta) = \mathbf{1}_z \left[\underline{J}_{11}(r) + \underline{J}_{123}(r,\Theta)\right] = \mathbf{1}_z\, \underline{J}_1(r,\Theta) \tag{1}$$

where current density $\underline{J}_{11}(r)$ take into account the skin effect and has a form

$$\underline{J}_{11}(r) = \frac{\underline{\Gamma}\,\underline{I}_1}{2\pi R_2} \frac{K_1(\underline{\Gamma}R_1)\,I_0(\underline{\Gamma}r) + I_1(\underline{\Gamma}R_1)\,K_0(\underline{\Gamma}r)}{I_1(\underline{\Gamma}R_2)\,K_1(\underline{\Gamma}R_1) - I_1(\underline{\Gamma}R_1)\,K_1(\underline{\Gamma}R_2)} = \frac{\underline{\Gamma}\,\underline{I}_1}{2\pi R_2}\,\underline{j}(r) \tag{2}$$

while

$$\underline{j}(r)=\frac{K_1(\underline{\Gamma}R_1)I_0(\underline{\Gamma}r)+I_1(\underline{\Gamma}R_1)K_0(\underline{\Gamma}r)}{I_1(\underline{\Gamma}R_2)K_1(\underline{\Gamma}R_1)-I_1(\underline{\Gamma}R_1)K_1(\underline{\Gamma}R_2)} \tag{2a}$$

and current density $\underline{J}_{12}(r,\Theta)$ is defined by formula

$$\underline{J}_{12}(r,\Theta)=-\frac{\underline{\Gamma}\,\underline{I}_2}{\pi R_2}\sum_{n=1}^{\infty}\left(\frac{R_2}{d}\right)^n \underline{f}_n(r)\cos n\Theta \tag{3}$$

where

$$\underline{f}_n(r)=\frac{K_{n+1}(\underline{\Gamma}R_1)I_n(\underline{\Gamma}r)+I_{n+1}(\underline{\Gamma}R_1)K_n(\underline{\Gamma}r)}{I_{n-1}(\underline{\Gamma}R_2)K_{n+1}(\underline{\Gamma}R_1)-I_{n+1}(\underline{\Gamma}R_1)K_{n-1}(\underline{\Gamma}R_2)} \tag{3a}$$

but current density $\underline{J}_{13}(r,\Theta)$

$$\underline{J}_{13}(r,\Theta)=-\frac{\underline{\Gamma}\,\underline{I}_3}{\pi R_2}\sum_{n=1}^{\infty}\left(\frac{R_2}{2d}\right)^n \underline{f}_n(r)\cos n\Theta = J_{13}(r,\Theta)\exp[\mathrm{j}\,\varphi_{J13}(r,\Theta)] \tag{4}$$

If currents

$$\underline{I}_2=\exp[-\mathrm{j}\frac{2}{3}\pi]\underline{I}_1 \quad \text{oraz} \quad \underline{I}_3=\exp[\mathrm{j}\frac{2}{3}\pi]\underline{I}_1 \tag{5}$$

then total current density in first conductor has a form

$$\underline{J}_1(r,\Theta)=\underline{J}_{11}(r)+\underline{J}_{123}(r,\Theta)=\frac{\underline{\Gamma}\,\underline{I}_1}{2\pi R_2}\left[\underline{j}(r)-2\sum_{n=1}^{\infty}\underline{A}_n\left(\frac{R_2}{d}\right)^n \underline{f}_n(r)\cos n\Theta\right] \tag{6}$$

where

$$\underline{A}_n=-\frac{1}{2}\left[\left(1+2^{-n}\right)+\mathrm{j}\sqrt{3}\left(1-2^{-n}\right)\right]=A_n\exp[\mathrm{j}\,\varphi_n] \tag{6a}$$

$$A_n=\sqrt{1-2^{-n}+4^{-n}} \tag{6b}$$

$$\varphi_n=-\pi+\operatorname{arctg}\frac{\sqrt{3}\left(1-2^{-n}\right)}{1+2^{-n}} \tag{6c}$$

Total eddy currents in second conductor is described by formula (6) in which current $\underline{I}_1$ should be replaced by $\underline{I}_2$ and constant $\underline{A}_n$ by constant

$$\underline{B}_n=\frac{1}{2}\left\{-\left[(-1)^n+1\right]+\mathrm{j}\sqrt{3}\left[(-1)^n-1\right]\right\}=B_n\exp[\mathrm{j}\,\psi_n] \tag{7}$$

For the third conductor, current $\underline{I}_1$ should be replaced by $\underline{I}_3$, but constant $\underline{A}_n$ by

$$\underline{C}_n=\frac{(-1)^n}{2}\left[-\left(1+2^{-n}\right)+\mathrm{j}\sqrt{3}\left(1-2^{-n}\right)\right]=C_n\exp[\mathrm{j}\,\vartheta_n] \tag{8}$$

Total magnetic field in the first conductor has a form [6, 7]

$$\underline{\boldsymbol{H}}_1(r,\Theta)=\underline{\boldsymbol{H}}_{11}(r)+\underline{\boldsymbol{H}}_{12}(r,\Theta)+\underline{\boldsymbol{H}}_{13}(r,\Theta)=\mathbf{1}_r\underline{H}_{1r}(r,\Theta)+\mathbf{1}_\Theta\underline{H}_{1\Theta}(r,\Theta) \quad (9)$$

where radial component

$$\underline{H}_{1r}(r,\Theta)=\underline{H}_{12r}(r,\Theta)+\underline{H}_{13r}(r,\Theta)=\underline{H}_{123r}(r,\Theta) \quad (10)$$

while

$$\underline{H}_{12r}(r,\Theta)=-\frac{\underline{I}_2}{\pi\,\underline{\Gamma}\,R_2\,r}\sum_{n=1}^{\infty}\left(\frac{R_2}{d}\right)^n n\,\underline{f}_n(r)\ \sin n\Theta \quad (10a)$$

and

$$\underline{H}_{13r}(r,\Theta)=-\frac{\underline{I}_3}{\pi\,\underline{\Gamma}\,R_2\,r}\sum_{n=1}^{\infty}\left(\frac{R_2}{2\,d}\right)^n n\,\underline{f}_n(r)\ \sin n\Theta \quad (10b)$$

Tangent component of magnetic field in first conductor

$$\underline{H}_{1\Theta}(r,\Theta)=\underline{H}_{11\Theta}(r)+\underline{H}_{12\Theta}(r,\Theta)+\underline{H}_{13\Theta}(r,\Theta)=\underline{H}_{11\Theta}(r)+\underline{H}_{123\Theta}(r,\Theta) \quad (11)$$

where

$$\underline{H}_{11\Theta}(r)=\frac{\underline{I}_1}{2\pi R_2}\frac{K_1(\underline{\Gamma}R_1)\,I_1(\underline{\Gamma}r)-I_1(\underline{\Gamma}R_1)\,K_1(\underline{\Gamma}r)}{I_1(\underline{\Gamma}R_2)\,K_1(\underline{\Gamma}R_1)-I_1(\underline{\Gamma}R_1)\,K_1(\underline{\Gamma}R_2)}=\frac{\underline{I}_1}{2\pi R_2}\underline{h}(r) \quad (11a)$$

$$\underline{h}(r)=\frac{K_1(\underline{\Gamma}R_1)\,I_1(\underline{\Gamma}r)-I_1(\underline{\Gamma}R_1)\,K_1(\underline{\Gamma}r)}{I_1(\underline{\Gamma}R_2)\,K_1(\underline{\Gamma}R_1)-I_1(\underline{\Gamma}R_1)\,K_1(\underline{\Gamma}R_2)} \quad (11b)$$

and

$$\underline{H}_{123\Theta}(r,\Theta)=-\frac{\underline{I}_1}{\pi\,\underline{\Gamma}\,R_2\,r}\sum_{n=1}^{\infty}\underline{A}_n\left(\frac{R_2}{d}\right)^n\left[-n\,\underline{f}_n(r)+\underline{g}_n(r)\right]\cos n\Theta \quad (11c)$$

$$\underline{g}_n(r)=\underline{\Gamma}\,r\,\frac{K_{n+1}(\underline{\Gamma}R_1)\,I_{n-1}(\underline{\Gamma}r)-I_{n+1}(\underline{\Gamma}R_1)\,K_{n-1}(\underline{\Gamma}r)}{I_{n-1}(\underline{\Gamma}R_2)\,K_{n+1}(\underline{\Gamma}R_1)-I_{n+1}(\underline{\Gamma}R_1)\,K_{n-1}(\underline{\Gamma}R_2)} \quad (11d)$$

In the same way we can determinate the magnetic field in second and third conductor.

In the above formulas $I_0(\underline{\Gamma}r)$, $K_0(\underline{\Gamma}r)$, $I_1(\underline{\Gamma}r)$, $K_1(\underline{\Gamma}r)$, $I_n(\underline{\Gamma}r)$, $K_n(\underline{\Gamma}r)$, $I_{n-1}(\underline{\Gamma}r)$, $K_{n-1}(\underline{\Gamma}r)$, $I_{n+1}(\underline{\Gamma}r)$ and $K_{n+1}(\underline{\Gamma}r)$ are modified Bessel's functions, 0, 1, n, n-1 and n+1 order, calculated for $r=R_1$ and $r=R_2$, and the complex propagation constant of electromagnetic wave

$$\underline{\Gamma}=\sqrt{\mathrm{j}\omega\mu\gamma}=\sqrt{\omega\mu\gamma}\,\exp[\mathrm{j}\frac{\pi}{4}]=k+\mathrm{j}\,k=\sqrt{2\mathrm{j}}\,k \quad (12)$$

in which attenuation constant

$$k = \sqrt{\frac{\omega\mu\gamma}{2}} = \frac{1}{\delta} \tag{12a}$$

where δ is the electrical skin depth of the electromagnetic wave penetration into the conducting environment, ω is an angular frequency, γ means conductivity of conductor, and $\mu_0 = 4\pi\,10^{-7}$ H·m^{-1} is magnetic permeability of the vacuum.

3. Influence of the external proximity effect on power losses in flat three phase high current busduct

Stream of the complex power penetrating into first conductor is defined by the formula [11]

$$\underline{\boldsymbol{S}}_{123}(r,\Theta) = \underline{\boldsymbol{E}}_{123}(r,\Theta) \times \underline{\boldsymbol{H}}^*_{123}(r,\Theta) \tag{13}$$

Apparent power of the first conductor is equal

$$\underline{S}_{123} = -\oiint_S \left[\underline{\boldsymbol{E}}_{123}(r) \times \underline{\boldsymbol{H}}^*_{123}(r)\right] \cdot \mathrm{d}\boldsymbol{S} = P_{123} + \mathrm{j}\,Q_{123} \tag{14}$$

from where a complex apparent power $\underline{S}_{123}$ in the first conductor has a form

$$\underline{S}_{123} = \frac{\mathrm{j}\,l\,I_1^2}{\pi\,\gamma\,R_2^2}\sum_{n=1}^{\infty} A_n^2 \left(\frac{R_2}{d}\right)^{2n} \left\{ \begin{array}{l} n\left[\underline{f}_n(R_1)\,\underline{f}^*_n(R_1) - \underline{f}_n(R_2)\,\underline{f}^*_n(R_2)\right] + \\ + \underline{f}_n(R_2)\,\underline{g}^*_n(R_2) - \underline{f}_n(R_1)\,\underline{g}^*_n(R_1) \end{array} \right\} \tag{15}$$

In the above formula we can not isolate the real part (as an active power) and the imaginary part (as a reactive power). It is impossible on account of the complex propagation constant and complex modified Bessel's functions. Therefore the active power will be calculated from formula [11]

$$P_{123} = \iiint_V \frac{1}{\gamma}\underline{J}_{123}(r)\,\underline{J}^*_{123}(r)\,\mathrm{d}V = \frac{1}{\gamma}\int_0^l \int_0^{2\pi} \int_{R_1}^{R_2} \underline{J}_{123}(r)\,\underline{J}^*_{123}(r)\,r\,\mathrm{d}r\,\mathrm{d}\Theta\,\mathrm{d}z \tag{16}$$

From the formula (16) we get

$$P_{123} = \frac{\underline{\Gamma}^*\,l\,I_1^2}{2\,\pi\,\gamma\,R_2}\sum_{n=1}^{\infty} A_n^2 \left(\frac{R_2}{d}\right)^{2n} \frac{\underline{a}_n}{\underline{b}_n\,\underline{b}^*_n} \tag{17}$$

where

$$\begin{aligned} \underline{a}_n = {} & I_{n+1}(\underline{\Gamma}R_2)\,K_{n+1}(\underline{\Gamma}R_1)\left[I^*_{n+1}(\underline{\Gamma}R_1)\,K^*_n(\underline{\Gamma}R_2) + I^*_n(\underline{\Gamma}R_2)\,K^*_{n+1}(\underline{\Gamma}R_1)\right] + \\ & + \mathrm{j}\,I_n(\underline{\Gamma}R_2)\,K_{n+1}(\underline{\Gamma}R_1)\left[I^*_{n+1}(\underline{\Gamma}R_2)\,K^*_{n+1}(\underline{\Gamma}R_1) - I^*_{n+1}(\underline{\Gamma}R_1)\,K^*_{n+1}(\underline{\Gamma}R_2)\right] - \\ & - I_{n+1}(\underline{\Gamma}R_1)\left\{ \begin{array}{l} K^*_{n+1}(\underline{\Gamma}R_1)\left[I^*_n(\underline{\Gamma}R_2)\,K_{n+1}(\underline{\Gamma}R_2) - \mathrm{j}\,I^*_{n+1}(\underline{\Gamma}R_2)\,K_n(\underline{\Gamma}R_2)\right] + \\ + I^*_{n+1}(\underline{\Gamma}R_1)\left[K^*_n(\underline{\Gamma}R_2)\,K_{n+1}(\underline{\Gamma}R_2) + \mathrm{j}\,K^*_{n+1}(\underline{\Gamma}R_2)\,K_n(\underline{\Gamma}R_2)\right] \end{array} \right\} \end{aligned} \tag{17a}$$

$$\underline{b}_n = I_{n-1}(\underline{\Gamma} R_2)\, K_{n+1}(\underline{\Gamma} R_1) - I_{n+1}(\underline{\Gamma} R_1)\, K_{n-1}(\underline{\Gamma} R_2) \tag{17b}$$

$$\underline{b}_n^{*} = I_{n-1}^{*}(\underline{\Gamma} R_2)\, K_{n+1}^{*}(\underline{\Gamma} R_1) - I_{n+1}^{*}(\underline{\Gamma} R_1)\, K_{n-1}^{*}(\underline{\Gamma} R_2) \tag{17c}$$

If we introduce the reference active power

$$P_0 = \frac{l\, I_1^2}{\pi\, \gamma\, (R_2^2 - R_1^2)} \tag{18}$$

then the relative active power in the first conductor has a form

$$k_{123}^{(P)} = \frac{P_{123}}{P_0} = \frac{-\mathrm{j}\sqrt{2\mathrm{j}}\,\alpha}{2}\left(1-\beta^2\right)\sum_{n=1}^{\infty} A_n^2 \left(\frac{1}{\lambda}\right)^{2n} \frac{\underline{a}_n}{\underline{b}_n\, \underline{b}_n^{*}} \tag{19}$$

where $\alpha = \dfrac{R_2}{\delta} = k\, R_2$, $\beta = \dfrac{R_1}{R_2}$ ($0 \le \beta \le 1$) and $\lambda = \dfrac{d}{R_2} \ge 1$.

Dependence of the coefficient (19) on parameter α for different values of the relative walls thickness β of the first conductor and of relative distance between conductors λ is presented in the Fig. 4.

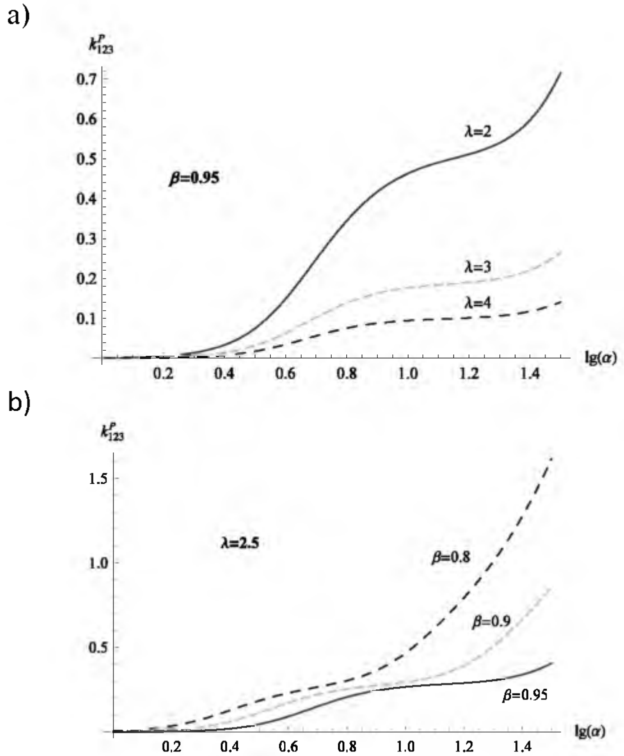


Fig. 4. Dependence of the relative active power in the first conductor on parameter α: a) for constant value of the parameter β, b) for constant of the parameter λ

The reactive power in the first conductor

$$Q_{123} = -\mathrm{j}\,(\underline{S}_{123} - P_{123}) = \frac{l\,I_2^2}{\pi\,\gamma\,R_2}\sum_{n=1}^{\infty} A_n^2\left(\frac{R_2}{d}\right)^{2n} \times$$
$$\times\left\{\begin{matrix} n\left[\underline{f}_n(R_1)\,\underline{f}_n^*(R_1) - \underline{f}_n(R_2)\,\underline{f}_n^*(R_2)\right] + \\ + \underline{f}_n(R_2)\,\underline{g}_n^*(R_2) - \underline{f}_n(R_1)\,\underline{g}_n^*(R_1) + \dfrac{\Gamma R_2}{2}\dfrac{\underline{a}_n}{\underline{b}_n\,\underline{b}_n^*} \end{matrix}\right\} \tag{20}$$

If we introduce the reference reactive power

$$Q_0 = X_{0w}\,I_1^2 = \omega\frac{\mu_0\,l}{2\,\pi}\left[\frac{R_1^4}{\left(R_2^2 - R_1^2\right)^2}\ln\frac{R_2}{R_1} - \frac{1}{4}\frac{3R_1^2 - R_2^2}{R_2^2 - R_1^2}\right]I_1^2 \tag{21}$$

then the relative reactive power of the first conductor has a form

$$k_{123}^{(Q)} = \frac{Q_{123}}{Q_0} = \frac{1}{\alpha^2\left[\dfrac{\beta^4}{\left(1-\beta^2\right)^2}\ln\dfrac{1}{\beta} - \dfrac{1}{4}\dfrac{3\beta^2 - 1}{1-\beta^2}\right]}\sum_{n=1}^{\infty} A_n^2\left(\frac{1}{\lambda}\right)^{2n} \times$$
$$\times\left\{\begin{matrix} n\left[\underline{f}_n(R_1)\,\underline{f}_n^*(R_1) - \underline{f}_n(R_2)\,\underline{f}_n^*(R_2)\right] + \\ + \underline{f}_n(R_2)\,\underline{g}_n^*(R_2) - \underline{f}_n(R_1)\,\underline{g}_n^*(R_1) + \dfrac{\sqrt{2\,\mathrm{j}}\,\alpha}{2}\dfrac{\underline{a}_n}{\underline{b}_n\,\underline{b}_n^*} \end{matrix}\right\} \tag{22}$$

Dependence of the coefficient (22) on parameter α for different values of the relative walls thickness β of the first conductor and of relative distance between conductors λ is presented in the Fig. 5.

In the same way we can calculated power losses in the second conductor. The relative active power in the second conductor has a form

$$k_{213}^{(P)} = \frac{P_{213}}{P_0} = \frac{-\mathrm{j}\sqrt{2\mathrm{j}}\,\alpha}{2}\left(1-\beta^2\right)\sum_{n=1}^{\infty} B_n^2\left(\frac{1}{\lambda}\right)^{2n}\frac{\underline{a}_n}{\underline{b}_n\,\underline{b}_n^*} \tag{23}$$

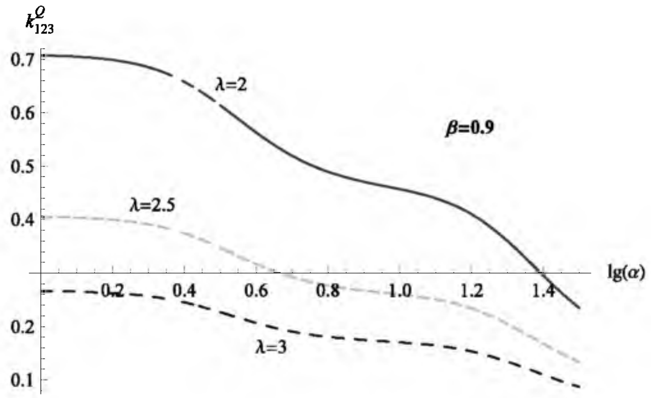
Dependence of the coefficient (23) on parameter α for different values of the relative walls thickness β of the second conductor and of relative distance between conductors λ is presented in the Fig. 6.

The relative reactive power of the second conductor has a form

$$k_{213}^{(Q)} = \frac{Q_{213}}{Q_0} = \frac{1}{\alpha^2 \left[\frac{\beta^4}{\left(1-\beta^2\right)^2} \ln\frac{1}{\beta} - \frac{1}{4}\frac{3\beta^2 - 1}{1-\beta^2} \right]} \sum_{n=1}^{\infty} B_n^2 \left(\frac{1}{\lambda}\right)^{2n} \times$$
$$\times \left\{ \begin{array}{l} n\left[\underline{f}_n(R_1)\,\underline{f}_n^*(R_1) - \underline{f}_n(R_2)\,\underline{f}_n^*(R_2)\right] + \\ + \underline{f}_n(R_2)\,\underline{g}_n^*(R_2) - \underline{f}_n(R_1)\,\underline{g}_n^*(R_1) + \frac{\sqrt{2\,\mathrm{j}}\,\alpha}{2}\frac{\underline{a}_n}{\underline{b}_n\,\underline{b}_n^*} \end{array} \right\} \tag{24}$$

Dependence of the coefficient (24) on parameter α for different values of the relative walls thickness β of the second conductor and of relative distance between conductors λ is presented in the Fig. 7.

a)



b)

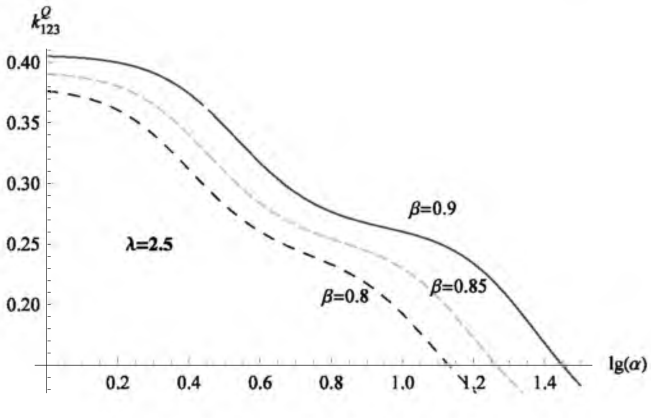


Fig. 5. Dependence of the relative reactive power of the first conductor on parameter α: a) for constant value of the parameter β, b) for constant of the parameter λ

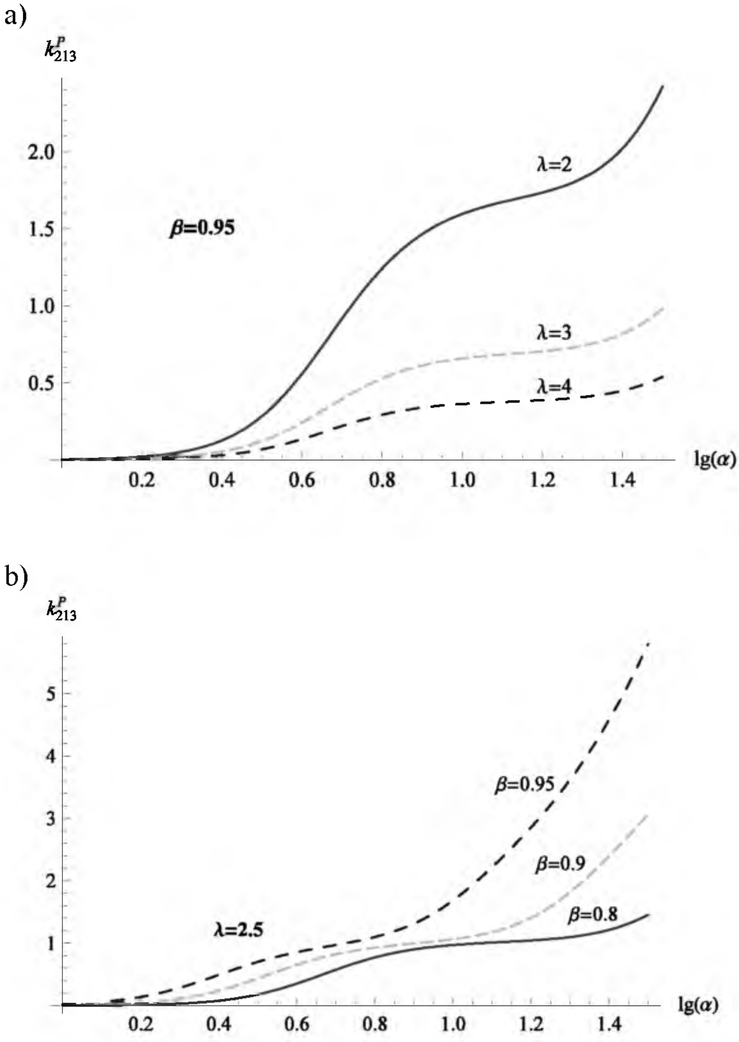


Fig. 6. Dependence of the relative active power in the second conductor on parameter α: a) for constant value of the parameter β, b) for constant of the parameter λ

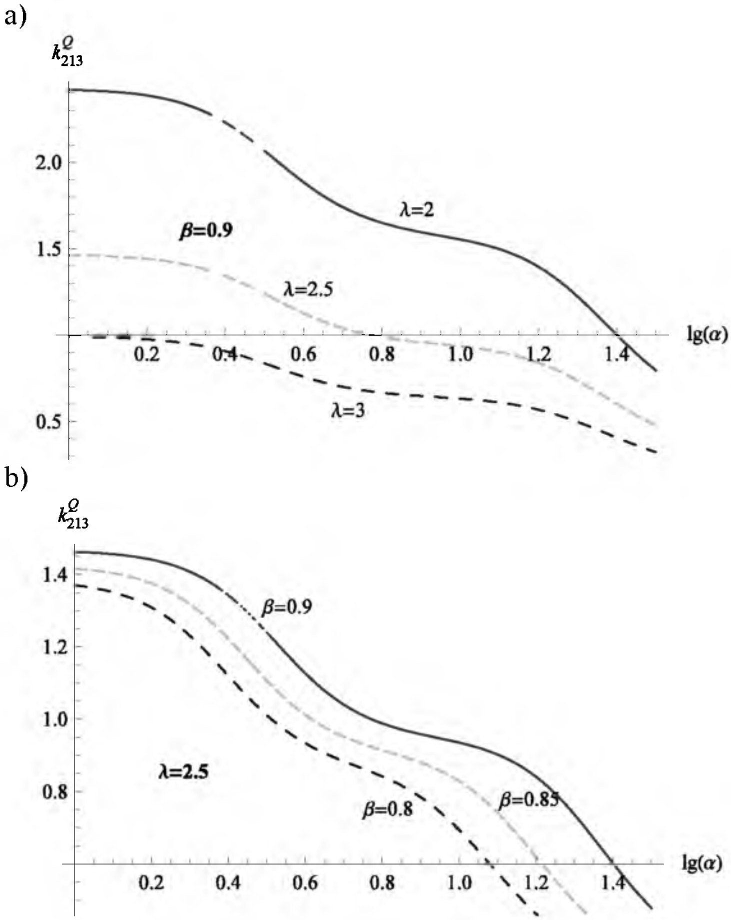


Fig. 7. Dependence of the relative reactive power of the second conductor on parameter α: a) for constant value of the parameter β, b) for constant of the parameter λ

In the case of third conductor we have

$$C_n = A_n = \sqrt{1-2^{-n}+4^{-n}} \tag{25}$$

hence

$$k_{312}^{(P)} = \frac{P_{312}}{P_0} = k_{123}^{(P)} \tag{26}$$

and

$$k_{312}^{(Q)} = \frac{Q_{312}}{Q_0} = k_{123}^{(Q)} \tag{27}$$

4. Conclusions

In produced high current busducts, for industrial frequency value of parameter α is included from 5 to 20. It means that active power in conductors of the flat three phase high current busduct can reach value of active power connected with phase current (Fig. 4). In the second conductor (Fig. 6) active power connected with proximity effect can be two times higher than active power of phase current. Similarly, reactive power connected with proximity effect in first and third conductor of three phase high current busduct can reach value reactive power of phase current (Fig. 5). But in second conductor reactive power connected with proximity effect is few times higher than reactive power of phase current (Fig. 7). In all determined causes proximity effect is stronger when distance between conductors is shorter.

References

[1] Nawrowski R.: *Tory wielkoprądowe izolowane powietrzem lub SF_6*. Wyd. Pol. Poznańskiej, Poznań 1998.

[2] CIGRE Brochure No 218.: *Gas Insulated Transmission Lines (GIL)*. WG 23/21/33-15, CIGRE, Paris, 2003.

[3] Piątek Z., Szczegielniak T., Kusiak D.: *Moc czynna i bierna bifilarnego toru wielkoprądowego,* XV ZKwE'2010, s. 35-36, Poznań 2010.

[4] Piątek Z., Szczegielniak T., Kusiak D.: *Wpływ zewnętrznego zjawiska zbliżenia na straty mocy w trójfazowym płaskim torze wielkoprądowym,* XVI ZKwE'2011, s. 35-36, Poznań 2011.

[5] Piątek Z.: *Impedances of Tubular High Current Busducts*. Series Progress in High-Voltage technique, Vol. 28, Polish Academy of Sciences, Committee of Electrical Engineering, Wyd. Pol. Częst., Czestochowa 2008.

[6] Kusiak D.: *Pole magnetyczne dwu i trójbiegunowych torów wielkoprądowych*. Rozprawa doktorska, Pol. Częst., Wydz. El., Częstochowa 2008.

[7] Piątek Z., Szczegielniak T., Kusiak D.: *Straty mocy w płaskim rurowym trójfazowym torze wielkopradowym*. Wiadomości Elektrotechniczne, LXXVII 2009 nr 11.

[8] Piątek Z., Kusiak D., Szczegielniak T.: *Pole magnetyczne trójfazowego płaskiego toru wielkoprądowego*, Zesz. Nauk. Pol. Śl. 2009, Elektryka, z. 1(209), ss. 51-65.

[9] Piątek Z., Kusiak D., Szczegielniak T.: *Reverse Reaction Magnetic Field in Flat Three Phase High Current Busduct*, XXXII IC-SPETO, s. 17-18, Gliwice-Ustroń 2009.

[10] Szuba M. i inni: *Linie i stacje elektroenergetyczne w środowisku człowieka*, Informator PSE-Operator S.A., Warszawa 2008.

[11] Krakowski M.: *Elektrotechnika teoretyczna. Pole elektromagnetyczne*. WN PWN, Warszawa 1995.