СПбГУТ им. проф. М.А. Бонч-Бруевича

Основы инфокоммуникационных систем

2016 г.

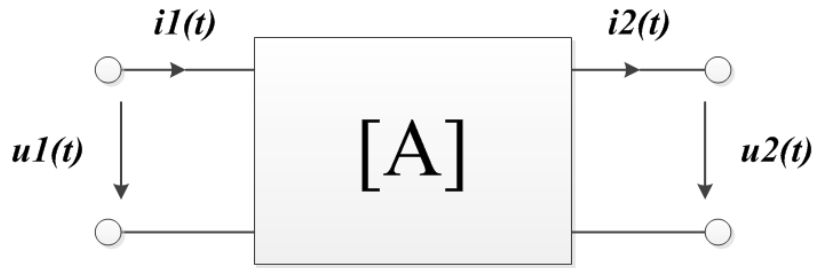
Физические каналы

Проводной канал

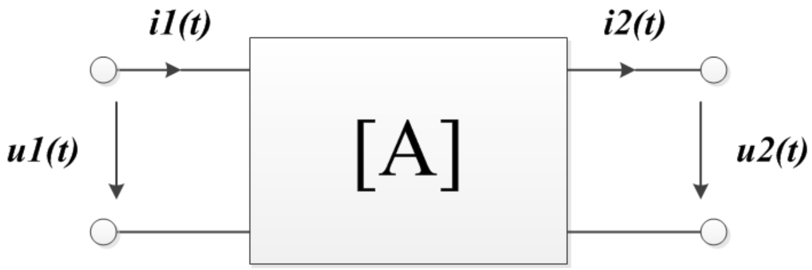
Основные понятия

Физический канал — ***естественная или искусственная*** среда распространения сигналов

Физический канал в виде линейного четырёхполюсника

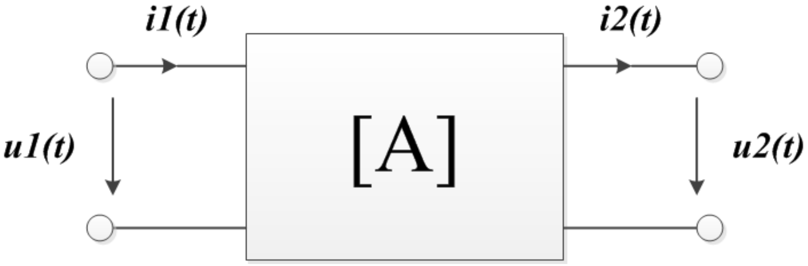


Физический канал в виде линейного четырёхполюсника



$$\begin{cases} u_1 = A_{11} \cdot u_2 + A_{12} \cdot i_2; \\ i_1 = A_{21} \cdot u_2 + A_{22} \cdot i_2 \end{cases}$$

Физический канал в виде линейного четырёхполюсника

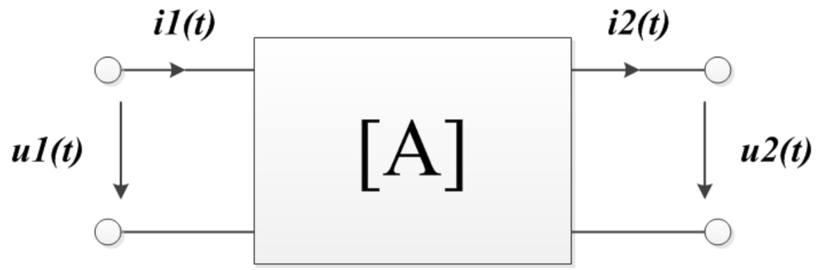


$$\begin{cases} u_1 = A_{11} \cdot u_2 + A_{12} \cdot i_2; \\ i_1 = A_{21} \cdot u_2 + A_{22} \cdot i_2 \end{cases}$$

$$\begin{bmatrix} u_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \cdot \begin{bmatrix} u_2 \\ i_2 \end{bmatrix}$$

$$[\mathrm{A}] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$$

Физический канал в виде линейного четырёхполюсника



$$\begin{cases} u_1 = A_{11} \cdot u_2 + A_{12} \cdot i_2; \\ i_1 = A_{21} \cdot u_2 + A_{22} \cdot i_2 \end{cases}$$

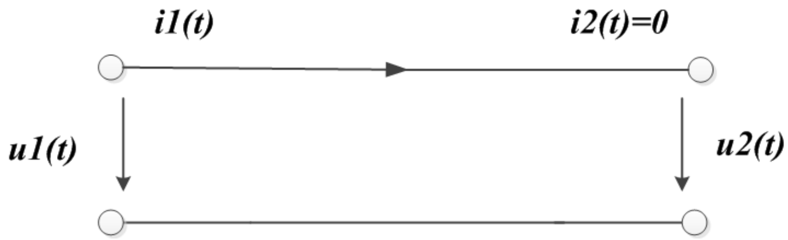
$$\begin{bmatrix} u_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \cdot \begin{bmatrix} u_2 \\ i_2 \end{bmatrix}$$

$$[\mathrm{A}] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$$

$$A_{11} = \left.\frac{u_1}{u_2}\right|_{i_2=0} \qquad A_{12} = \left.\frac{u_1}{i_2}\right|_{u_2=0} \quad \text{Ом}$$

$$A_{21} = \left.\frac{i_1}{u_2}\right|_{i_2=0} \quad \text{См} \qquad A_{22} = \left.\frac{i_1}{i_2}\right|_{u_2=0}$$

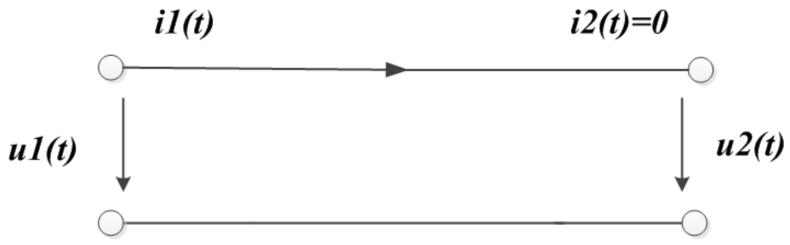
Физический канал в виде линейного четырёхполюсника

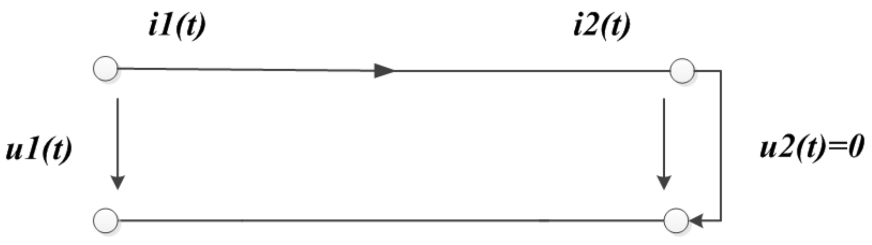


$$A_{11} = \left.\frac{u_1}{u_2}\right|_{i_2=0} = 1; \qquad u_1 = u_2;$$

$$A_{21} = \left.\frac{i_1}{u_2}\right|_{i_2=0} = 0; \qquad i_1 = 0;$$

Физический канал в виде линейного четырёхполюсника





$$A_{11} = \left.\frac{u_1}{u_2}\right|_{i_2=0} =1; \qquad u_1 = u_2;$$

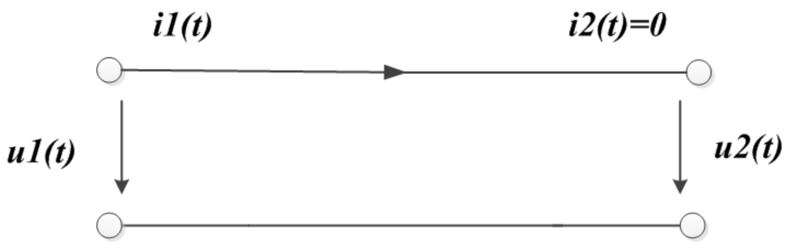
$$A_{12} = \left.\frac{u_1}{i_2}\right|_{u_2=0} =0; \qquad u_1 = u_2 =0;$$

$$A_{21} = \left.\frac{i_1}{u_2}\right|_{i_2=0} =0; \qquad i_1 = 0;$$

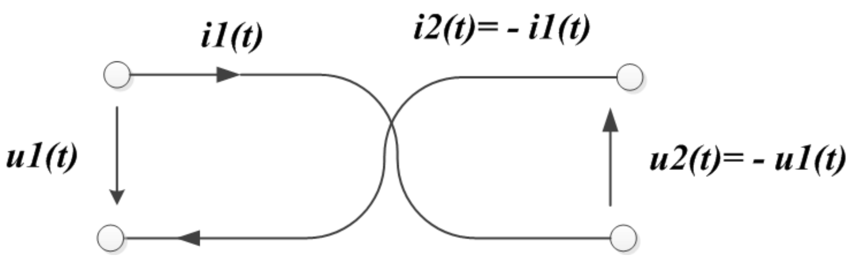
$$A_{22} = \left.\frac{i_1}{i_2}\right|_{u_2=0} =1; \qquad i_1 = i_2;$$

$$[\mathrm{A}] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \qquad \Delta A = 1;$$

Пример физического канала



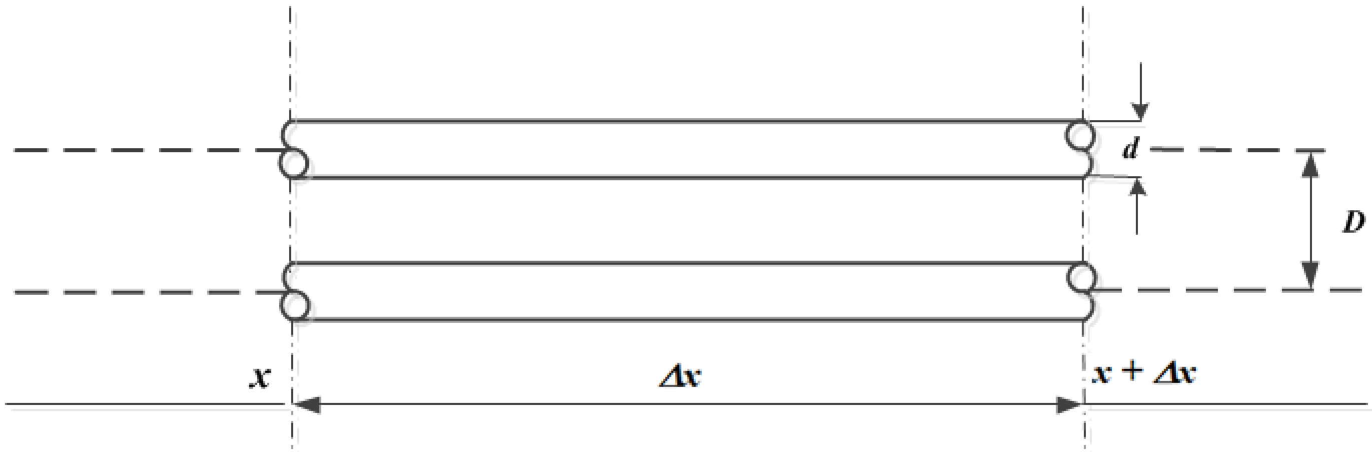
"Витая пара"



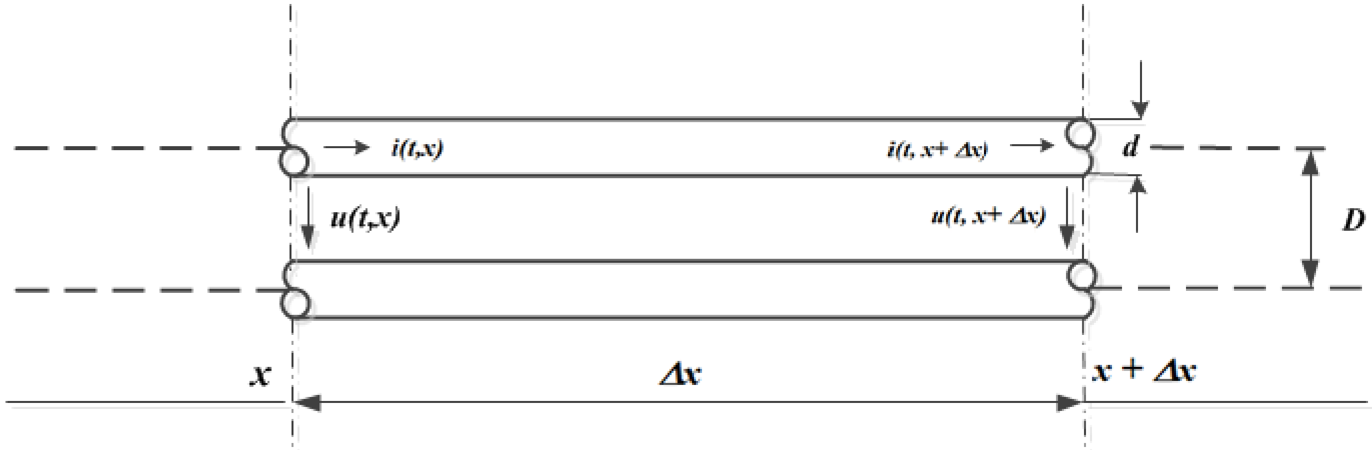
$$[A]=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}; \quad \Delta A = 1;$$

$$[A]=\begin{bmatrix}-1 & 0\\ 0 & -1\end{bmatrix}; \quad \Delta A = 1;$$

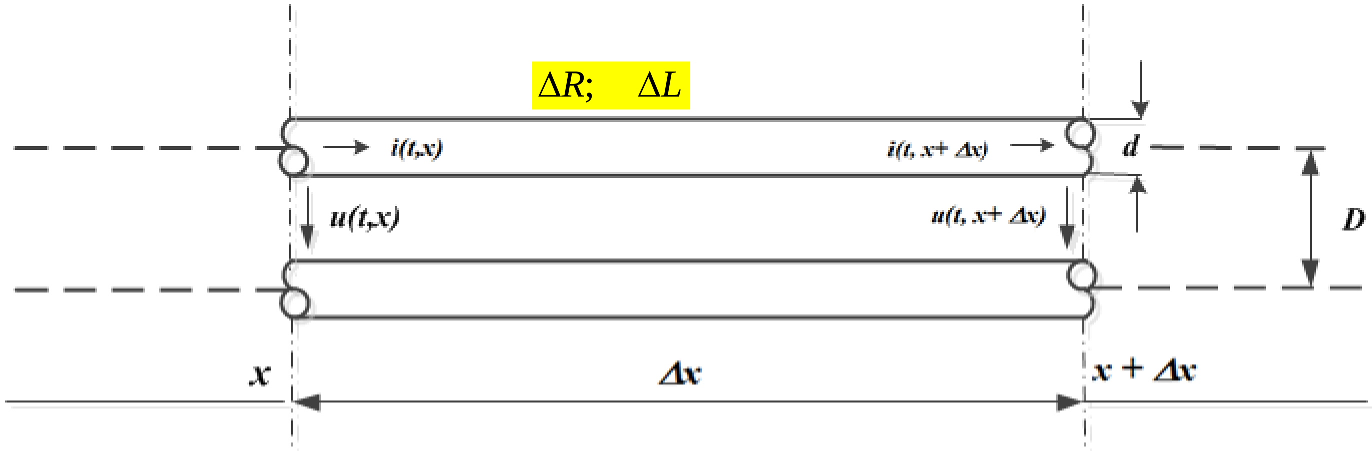
Проводной канал



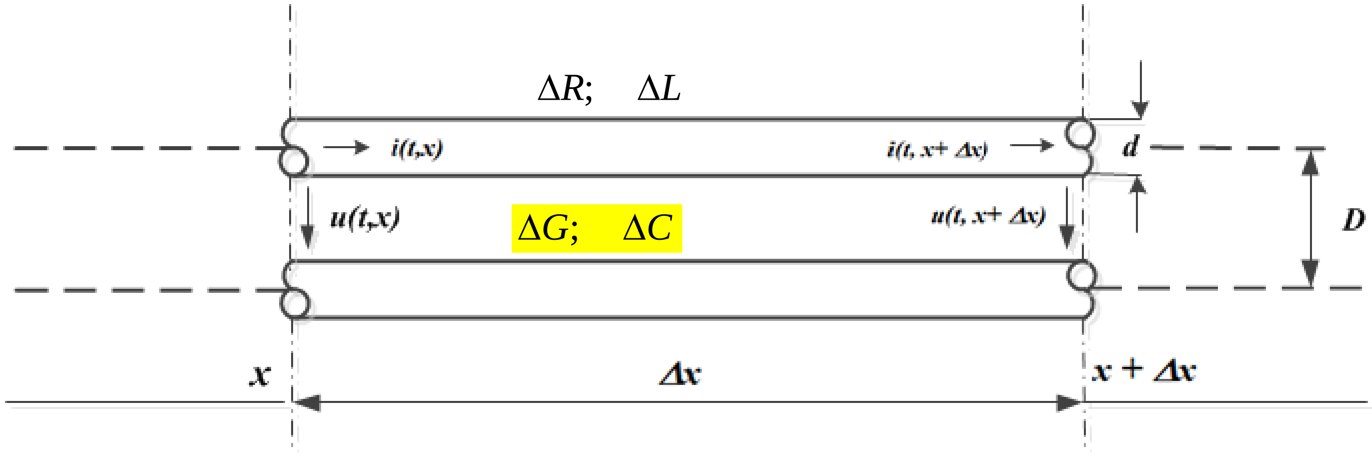
Проводной канал



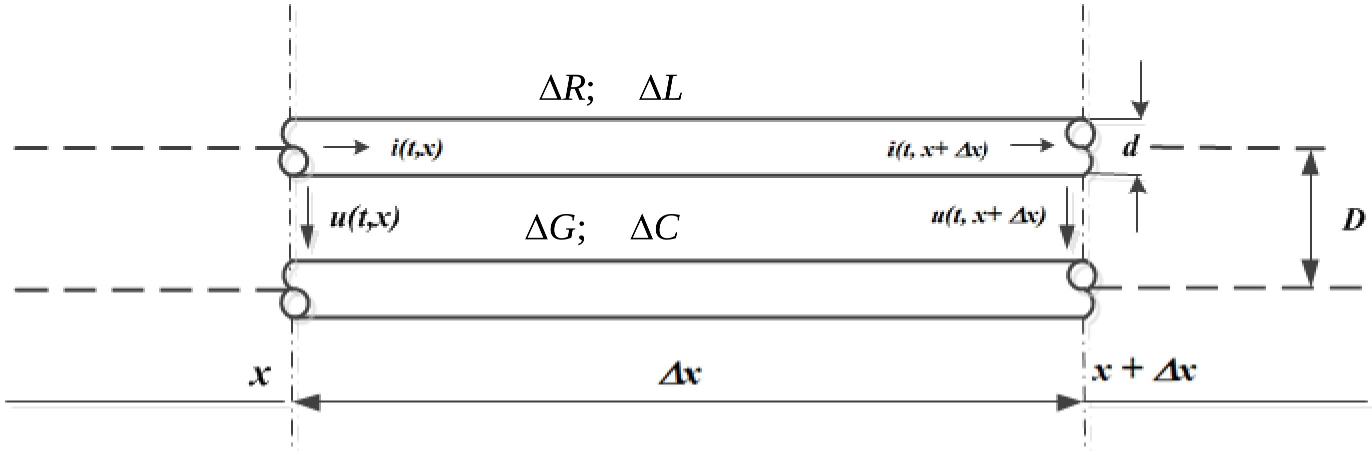
Проводной канал



Проводной канал

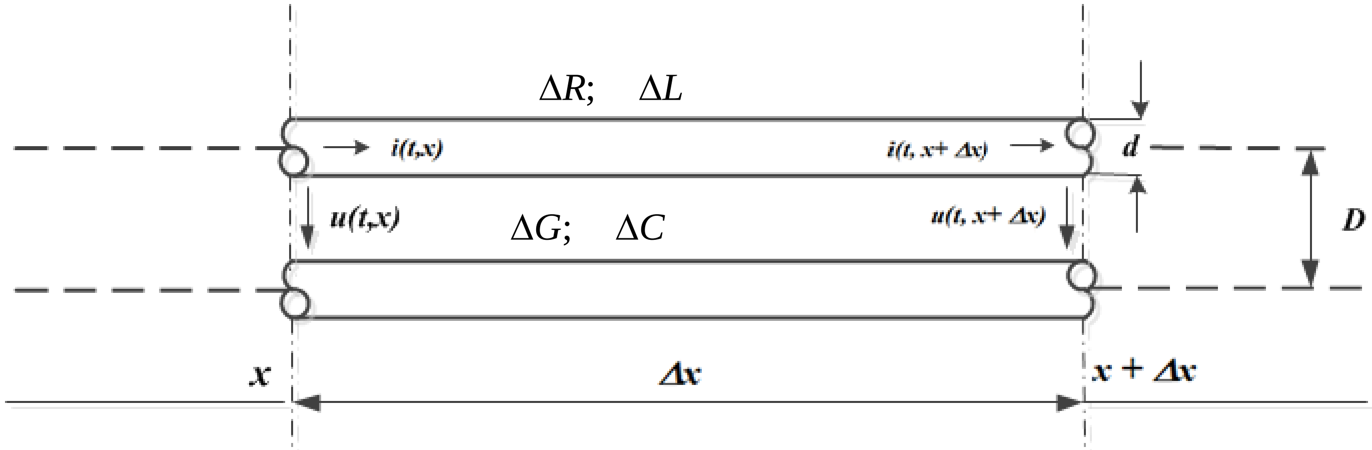


Проводной канал



$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

Проводной канал



$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

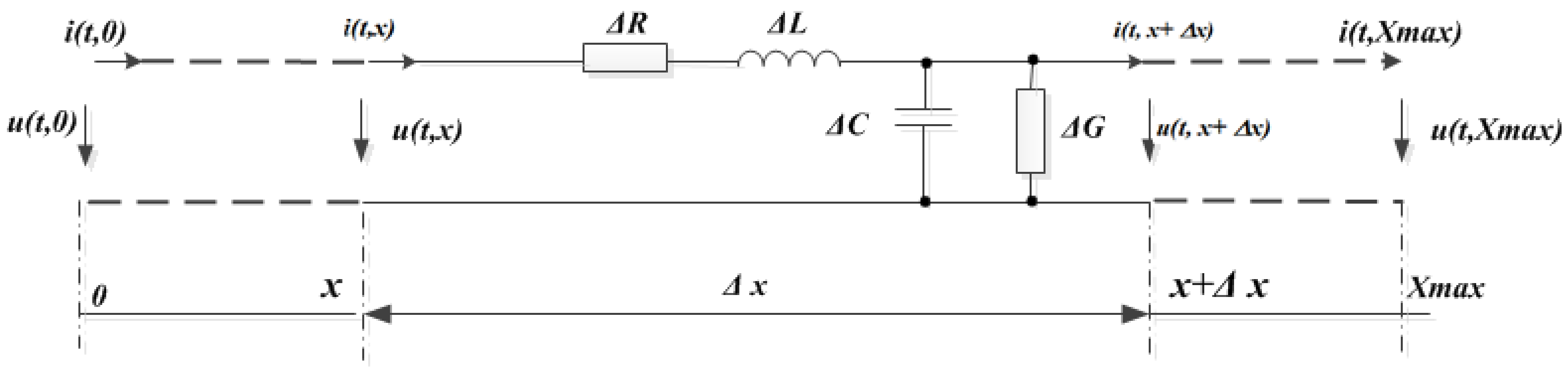
$$R_0 = \rho \cdot \frac{2}{S} = \frac{2 \cdot \rho}{\pi \cdot d^2}; \quad L_0 = \mu \cdot \lg(\frac{2 \cdot D}{d}); \quad C_0 = \frac{\varepsilon}{\lg(\frac{2 \cdot D}{d})}; \quad G_0 = 2 \cdot \pi \cdot f \cdot C_0 \cdot tg(\delta);$$

$$R_0 \left\langle \frac{Ом}{м} \right\rangle; \quad L_0 \left\langle \frac{Гн}{м} \right\rangle; \quad C_0 \left\langle \frac{Ф}{м} \right\rangle; \quad G_0 \left\langle \frac{См}{м} \right\rangle;$$

$$\rho \left\langle \frac{Ом}{м} \right\rangle; \quad \mu \left\langle \frac{Гн}{м} \right\rangle; \quad \varepsilon \left\langle \frac{Ф}{м} \right\rangle; \quad \delta \left\langle град \right\rangle$$

удельное сопротивление | магнитная проницаемость | диэлектрическая проницаемость | угол потерь в диэлектрике

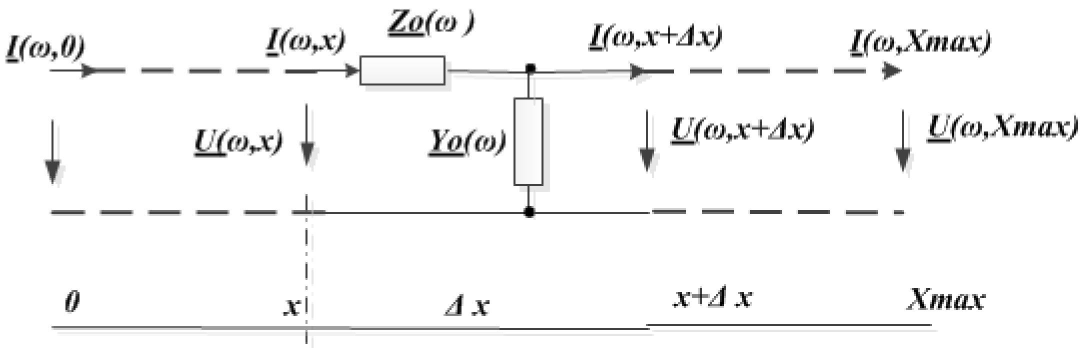
Проводной канал



$$\underline{Z_0}(\omega) = [j \cdot \omega \cdot L_0 + R_0] \quad \left\langle \frac{Ом}{м} \right\rangle;$$

$$\underline{Y_0}(\omega) = [j \cdot \omega \cdot C_0 + G_0] \quad \left\langle \frac{См}{м} \right\rangle;$$

Проводной канал



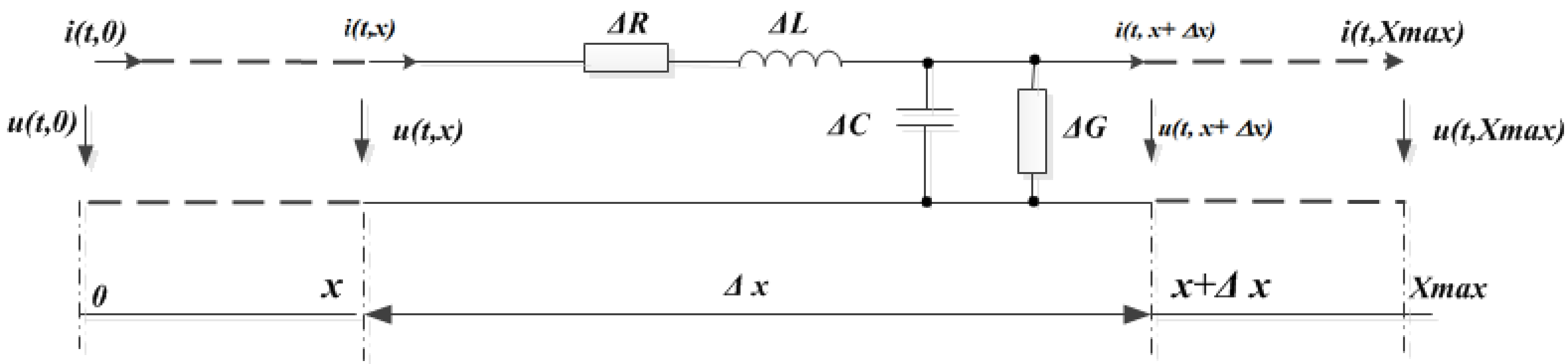
$$\underline{\gamma}_0(\omega) = \sqrt{\underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega)}; \quad \left\langle \frac{1}{м} \right\rangle;$$

$\underline{\gamma}_0(\omega)$ - постоянная распространения

$$\frac{\underline{\underline{Z}}_0(\omega)}{\underline{\gamma}_0(\omega)} = \sqrt{\frac{\underline{\underline{Z}}_0(\omega)}{\underline{Y}_0(\omega)}} = \underline{Z}_w(\omega) \quad \langle Ом \rangle;$$

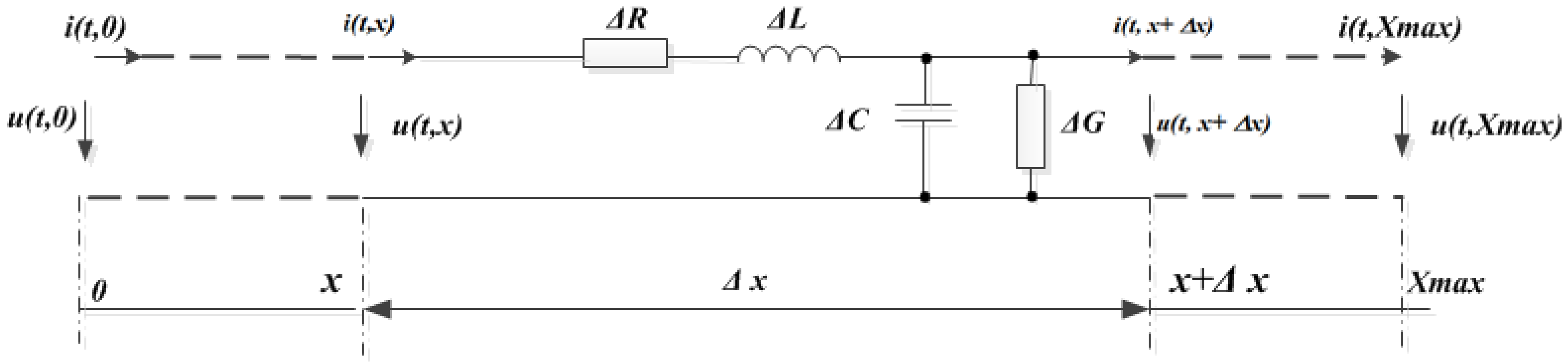
$\underline{Z}_w(\omega)$ - волновое сопротивление

Проводной канал



$$\begin{cases} \Delta \underline{U}(\omega, x) = \underline{U}(\omega, x) - \underline{U}(\omega, x + \Delta x) = \underline{Z_0}(\omega) \cdot \Delta x \cdot \underline{I}(\omega, x) \\ \Delta \underline{I}(\omega, x) = \underline{I}(\omega, x) - \underline{I}(\omega, x + \Delta x) = \underline{Y_0}(\omega) \cdot \Delta x \cdot \underline{U}(\omega, x + \Delta x) \end{cases}$$

Проводной канал



$$\begin{cases} \Delta\underline{U}(\omega,x) = \underline{U}(\omega,x) - \underline{U}(\omega,x+\Delta x) = \underline{Z}_0(\omega)\cdot\Delta x\cdot\underline{I}(\omega,x) \\ \Delta\underline{I}(\omega,x) = \underline{I}(\omega,x) - \underline{I}(\omega,x+\Delta x) = \underline{Y}_0(\omega)\cdot\Delta x\cdot\underline{U}(\omega,x+\Delta x) \end{cases}$$

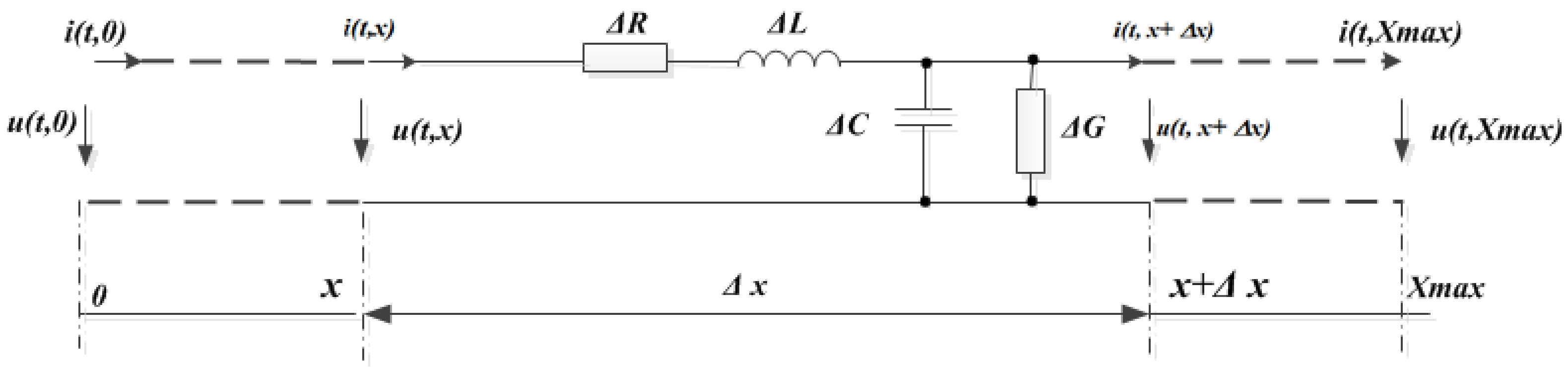
$$\Delta x \to 0:$$

$$\Delta x = \partial x:$$

$$\Delta\underline{I}(\omega,x) = \partial\underline{I}(\omega,x);$$

$$\Delta\underline{U}(\omega,x) = \partial\underline{U}(\omega,x);$$

Проводной канал



$$\begin{cases} \Delta\underline{U}(\omega,x) = \underline{U}(\omega,x) - \underline{U}(\omega,x+\Delta x) = \underline{Z_0}(\omega)\cdot\Delta x\cdot\underline{I}(\omega,x) \\ \Delta\underline{I}(\omega,x) = \underline{I}(\omega,x) - \underline{I}(\omega,x+\Delta x) = \underline{Y_0}(\omega)\cdot\Delta x\cdot\underline{U}(\omega,x+\Delta x) \end{cases}$$

$$\Delta x \to 0:$$

$$\Delta x = \partial x:$$

$$\Delta\underline{I}(\omega,x) = \partial\underline{I}(\omega,x);$$

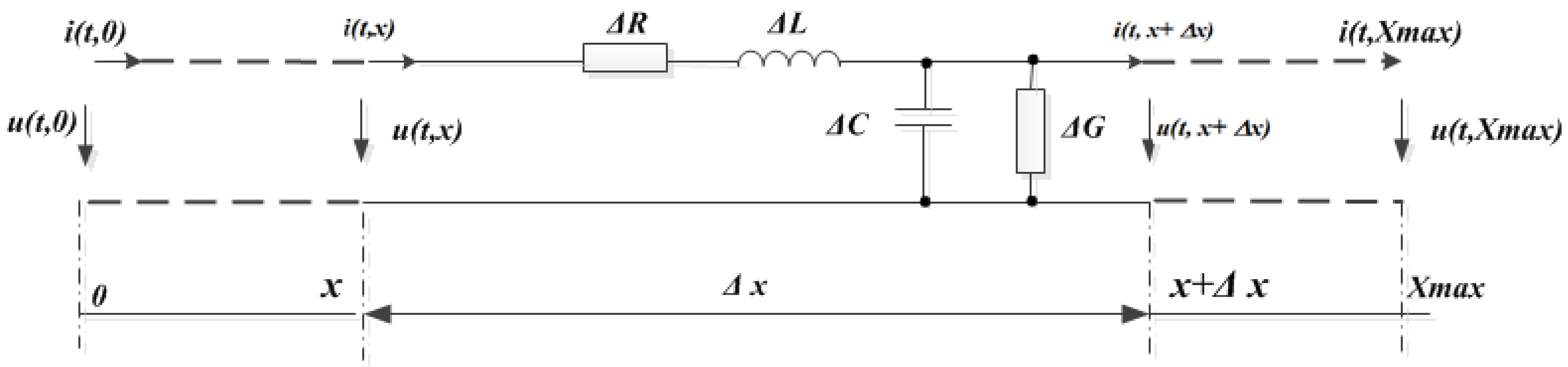
$$\Delta\underline{U}(\omega,x) = \partial\underline{U}(\omega,x);$$

$$\underline{U}(\omega,x+\Delta x) \approx \underline{U}(\omega,x);$$

$$\underline{I}(\omega,x+\Delta x) \approx \underline{I}(\omega,x);$$

$$\begin{cases} \dfrac{\partial\underline{U}(\omega,x)}{\partial x} = -\underline{Z_0}(\omega)\cdot\underline{I}(\omega,x); \\ \dfrac{\partial\underline{I}(\omega,x)}{\partial x} = -\underline{Y_0}(\omega)\cdot\underline{U}(\omega,x); \\ \underline{U_0} = \underline{U}(\omega,0); \qquad \underline{I_0} = \underline{I}(\omega,0); \end{cases}$$

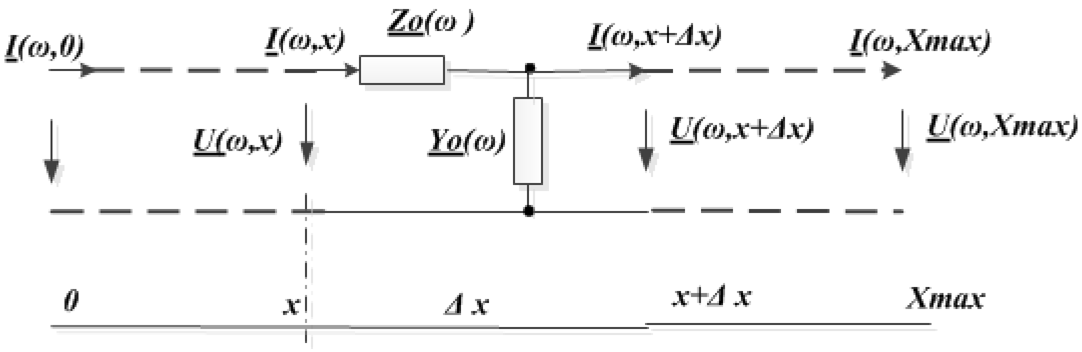
Проводной канал



$$\begin{cases} \dfrac{\partial \underline{U}(\omega, x)}{\partial x} = -\underline{Z}_0(\omega)\cdot \underline{I}(\omega, x); \\ \dfrac{\partial \underline{I}(\omega, x)}{\partial x} = -\underline{Y}_0(\omega)\cdot \underline{U}(\omega, x); \\ \underline{U}_0 = \underline{U}(\omega, 0); \qquad \underline{I}_0 = \underline{I}(\omega, 0); \end{cases}$$

$$\begin{cases} \dfrac{\partial^2 \underline{U}(\omega, x)}{\partial x^2} = \underline{Z}_0(\omega)\cdot \underline{Y}_0(\omega)\cdot \underline{U}(\omega, x); \\ \dfrac{\partial^2 \underline{I}(\omega, x)}{\partial x^2} = \underline{Z}_0(\omega)\cdot \underline{Y}_0(\omega)\cdot \underline{I}(\omega, x); \\ \underline{U}_0 = \underline{U}(\omega, 0); \qquad \underline{I}_0 = \underline{I}(\omega, 0); \end{cases}$$

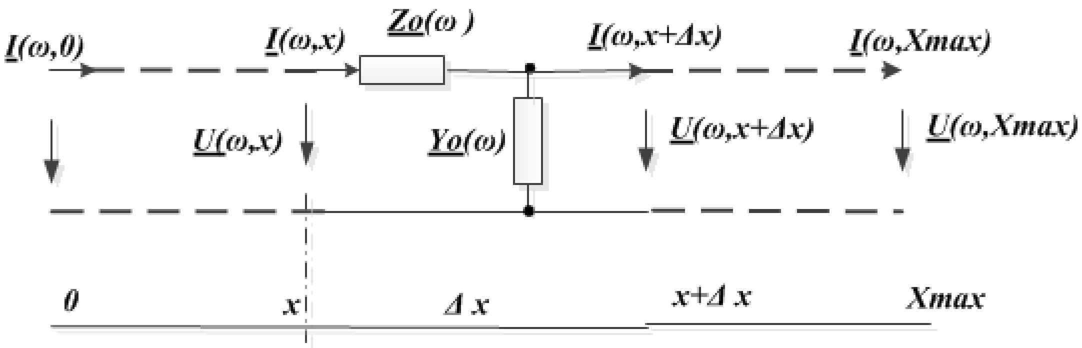
Проводной канал



$$\underline{Z}_0(\omega)=\left[\,j\cdot\omega\cdot L_0+R_0\right]\ \left\langle\frac{Ом}{м}\right\rangle; \qquad \underline{Y}_0(\omega)=\left[\,j\cdot\omega\cdot C_0+G_0\right]\ \left\langle\frac{См}{м}\right\rangle$$

$$\underline{\gamma}_0(\omega)=\sqrt{\underline{Z}_0(\omega)\cdot\underline{Y}_0(\omega)}\ \left\langle\frac{1}{м}\right\rangle; \qquad \underline{Z}_w(\omega)=\sqrt{\frac{\underline{Z}_0(\omega)}{\underline{Y}_0(\omega)}}\ \left\langle Ом\right\rangle;$$

Проводной канал

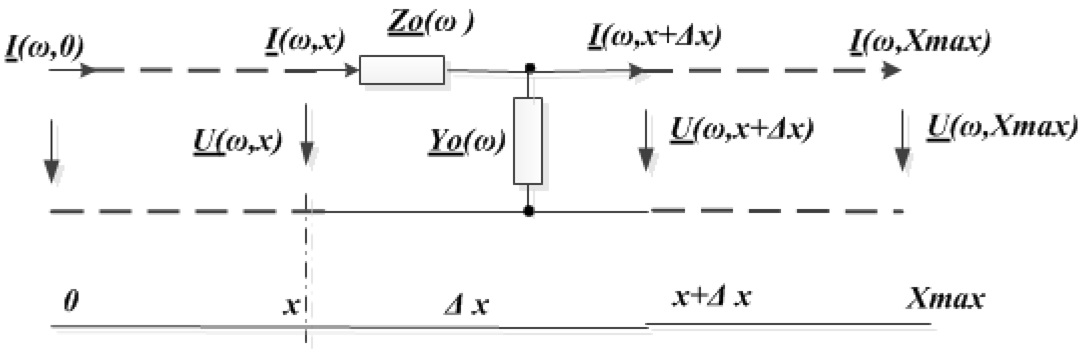


$$\underline{Z}_0(\omega) = [j \cdot \omega \cdot L_0 + R_0] \quad \left\langle \frac{Ом}{м} \right\rangle; \qquad \underline{Y}_0(\omega) = [j \cdot \omega \cdot C_0 + G_0] \quad \left\langle \frac{См}{м} \right\rangle$$

$$\underline{\gamma}_0(\omega) = \sqrt{\underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega)} \quad \left\langle \frac{1}{м} \right\rangle; \qquad \underline{Z}_w(\omega) = \sqrt{\frac{\underline{Z}_0(\omega)}{\underline{Y}_0(\omega)}} \quad \langle Ом \rangle;$$

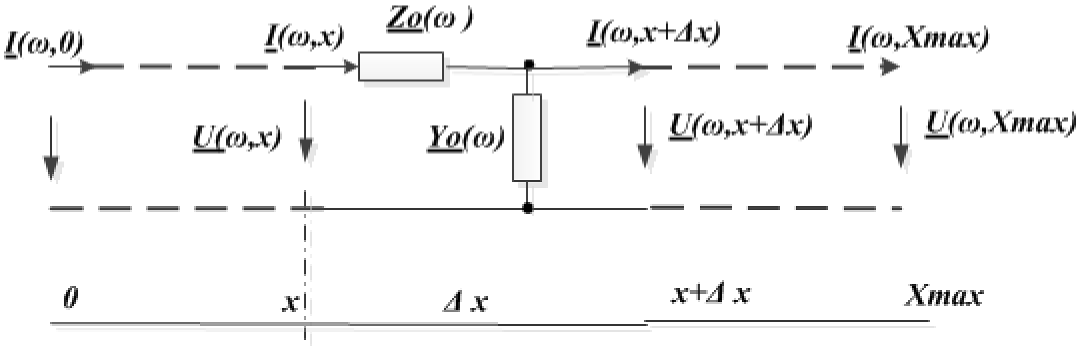
$$\begin{cases} \dfrac{\partial^2 \underline{U}(\omega, x)}{\partial x^2} = \underline{\gamma}_0^2(\omega) \cdot \underline{U}(\omega, x); \\ \dfrac{\partial^2 \underline{I}(\omega, x)}{\partial x^2} = \underline{\gamma}_0^2(\omega) \cdot \underline{I}(\omega, x); \\ \underline{U}_0 = \underline{U}(\omega, 0); \qquad \underline{I}_0 = \underline{I}(\omega, 0); \end{cases}$$

Проводной канал



$$\begin{cases} \underline{U}(\omega,x) = \underline{U}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - \underline{Z_w}(\omega)\cdot \underline{I}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,x) = \underline{I}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - \dfrac{1}{\underline{Z_w}(\omega)}\cdot \underline{U}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

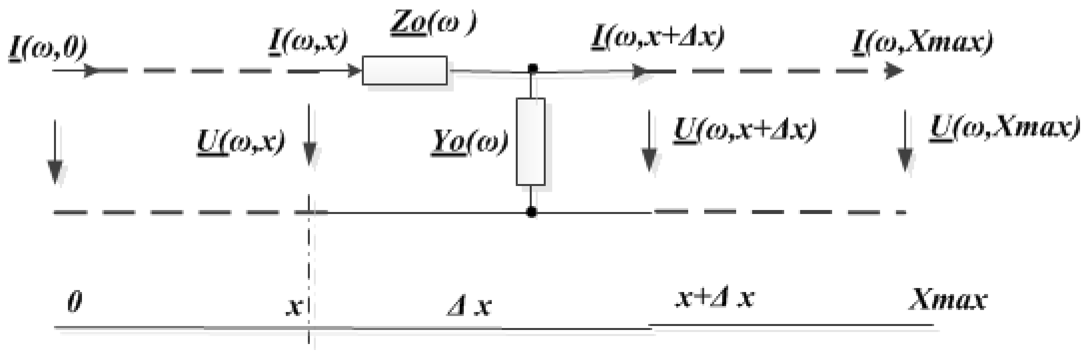
Проводной канал



$$\begin{cases} \underline{U}(\omega,x) = \underline{U}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - \underline{Z_w}(\omega)\cdot \underline{I}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,x) = \underline{I}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - \dfrac{1}{\underline{Z_w}(\omega)}\cdot \underline{U}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega,0) = \underline{U}(\omega,x)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] + \underline{Z_w}(\omega)\cdot \underline{I}(\omega,x)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,0) = \dfrac{1}{\underline{Z_w}(\omega)}\cdot \underline{U}(\omega,x)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right] + \underline{I}(\omega,x)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

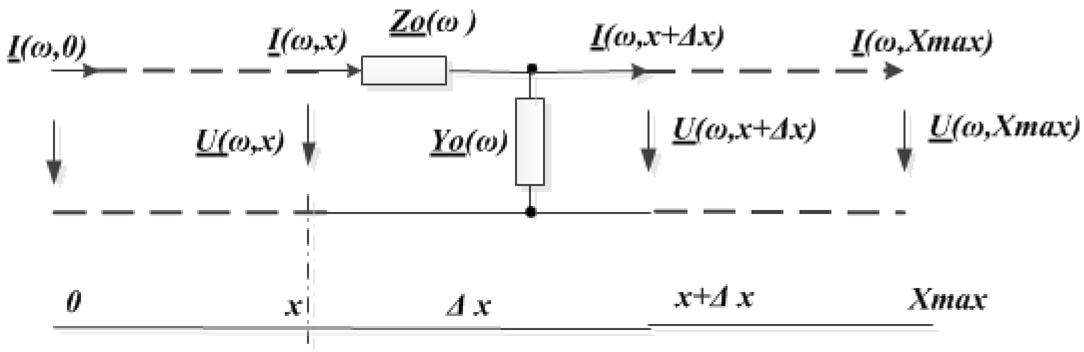
Проводной канал



$$\begin{cases} \underline{U}(\omega,0) = \underline{U}(\omega,x)\cdot ch\left[\underline{\gamma}_0(\omega)\cdot x\right] + \underline{Z}_w(\omega)\cdot \underline{I}(\omega,x)\cdot sh\left[\underline{\gamma}_0(\omega)\cdot x\right]; \\ \underline{I}(\omega,0) = \dfrac{1}{\underline{Z}_w(\omega)}\cdot \underline{U}(\omega,x)\cdot sh\left[\underline{\gamma}_0(\omega)\cdot x\right] + \underline{I}(\omega,x)\cdot ch\left[\underline{\gamma}_0(\omega)\cdot x\right]; \end{cases}$$

$$\begin{bmatrix} \underline{U}(\omega,0) \\ \underline{I}(\omega,0) \end{bmatrix} = \begin{bmatrix} ch\left[\underline{\gamma}_0(\omega)\cdot x\right] & \underline{Z}_w(\omega)\cdot sh\left[\underline{\gamma}_0(\omega)\cdot x\right] \\ \dfrac{1}{\underline{Z}_w(\omega)}\cdot sh\left[\underline{\gamma}_0(\omega)\cdot x\right] & ch\left[\underline{\gamma}_0(\omega)\cdot x\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega,x) \\ \underline{I}(\omega,x) \end{bmatrix}$$

Проводной канал



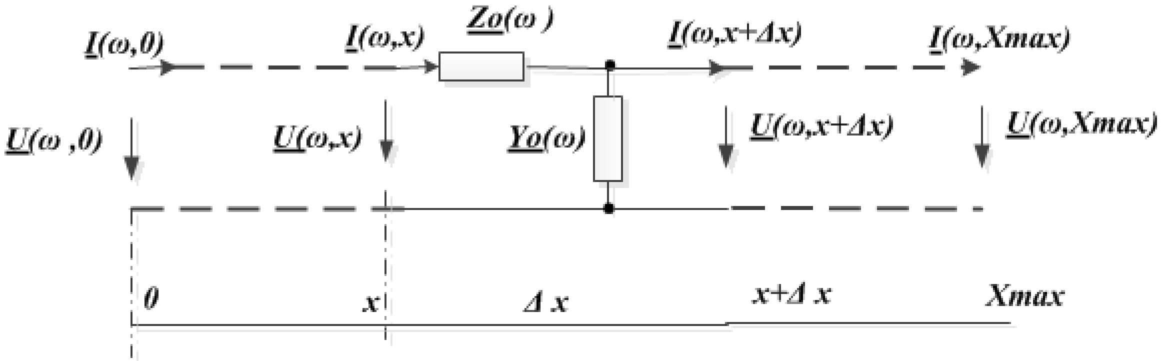
$$\begin{bmatrix} \underline{U}(\omega,0) \\ \underline{I}(\omega,0) \end{bmatrix} = \begin{bmatrix} ch\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right] & \underline{Z_w}(\omega)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right] \\ \dfrac{1}{\underline{Z_w}(\omega)}\cdot sh\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right] & ch\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, X_{\max}) \\ \underline{I}(\omega, X_{\max}) \end{bmatrix};$$

$$\underline{A_{11}}(\omega) = ch\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right]; \qquad \underline{A_{12}}(\omega) = \underline{Z_w}(\omega)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right];$$

$$\underline{A_{21}}(\omega) = \frac{1}{\underline{Z_w}(\omega)}\cdot sh\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right]; \qquad \underline{A_{22}}(\omega) = ch\left[\underline{\gamma_0}(\omega)\cdot X_{\max}\right];$$

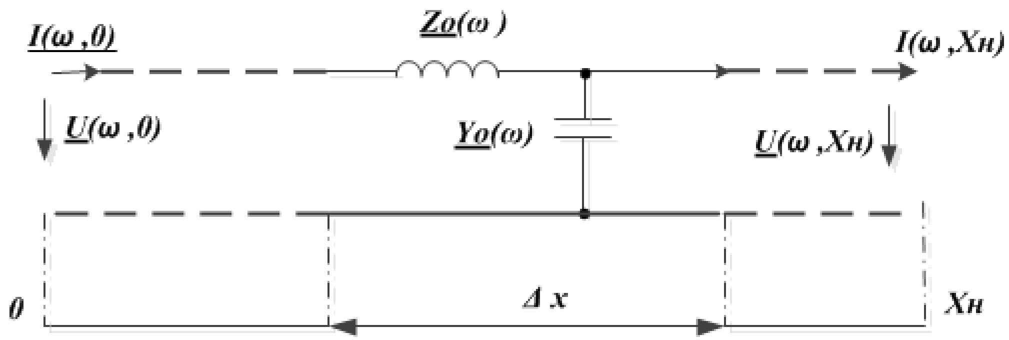
$$\Delta A = \underline{A_{11}}(\omega)\cdot\underline{A_{22}}(\omega) - \underline{A_{21}}(\omega)\cdot\underline{A_{22}}(\omega) = 1$$

Проводной канал без потерь



$$R_0 = 0; \qquad G_0 = 0;$$

Проводной канал без потерь

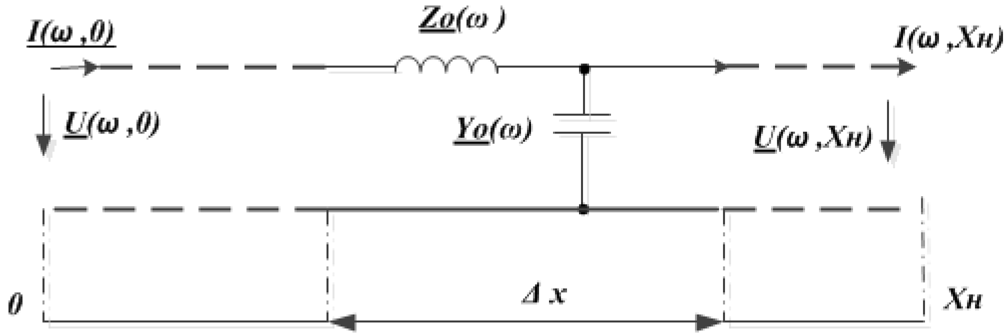


$$R_0 = 0; \qquad G_0 = 0;$$

$$\underline{Z_0}(\omega) = j \cdot \omega \cdot L_0 \quad \left\langle \frac{Ом}{м} \right\rangle; \qquad \underline{Y_0}(\omega) = j \cdot \omega \cdot C_0 \quad \left\langle \frac{См}{м} \right\rangle;$$

$$Z_w = \sqrt{\frac{L_0}{C_0}} \quad \langle Ом \rangle; \qquad \underline{\gamma_0}(\omega) = j \cdot \omega \sqrt{L_0 \cdot C_0} \quad \left\langle \frac{1}{м} \right\rangle;$$

Проводной канал без потерь



$R_0 = 0; \qquad G_0 = 0;$

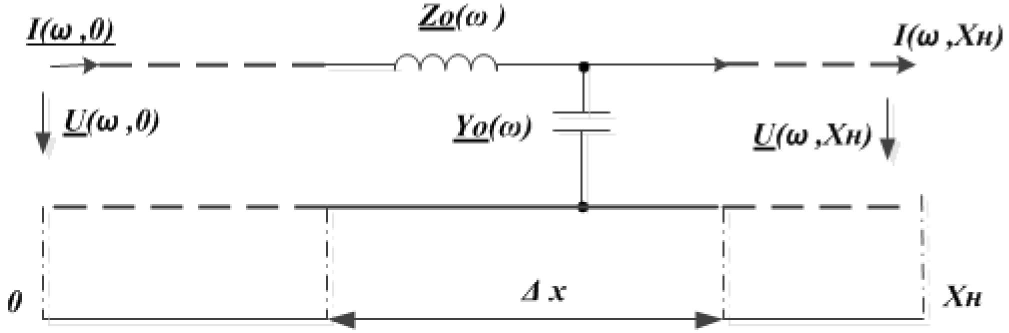
$$\underline{Z_0}(\omega) = j \cdot \omega \cdot L_0 \quad \left\langle \frac{Ом}{м} \right\rangle; \qquad \underline{Y_0}(\omega) = j \cdot \omega \cdot C_0 \quad \left\langle \frac{См}{м} \right\rangle;$$

$$Z_w = \sqrt{\frac{L_0}{C_0}} \quad \langle Ом \rangle; \qquad \underline{\gamma_0}(\omega) = j \cdot \omega \sqrt{L_0 \cdot C_0} \quad \left\langle \frac{1}{м} \right\rangle;$$

$$\frac{1}{\sqrt{L_0 \cdot C_0}} \qquad \frac{1}{\sqrt{\frac{Гн}{м} \cdot \frac{Ф}{м}}} = \frac{м}{\sqrt{Гн \cdot Ф}} = \frac{м}{с}$$ - скорость !!!; $$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

скорость распространения колебаний в физическом канале

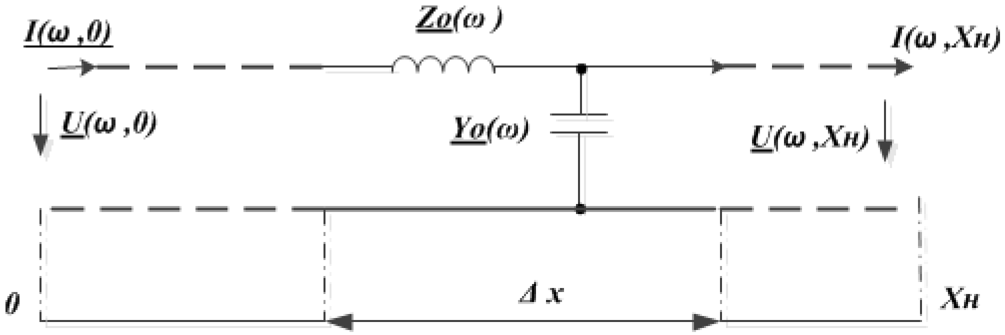
Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

$$L_0 = \mu \cdot \lg(\frac{2 \cdot D}{d}); \qquad C_0 = \frac{\varepsilon}{\lg(\frac{2 \cdot D}{d})};$$

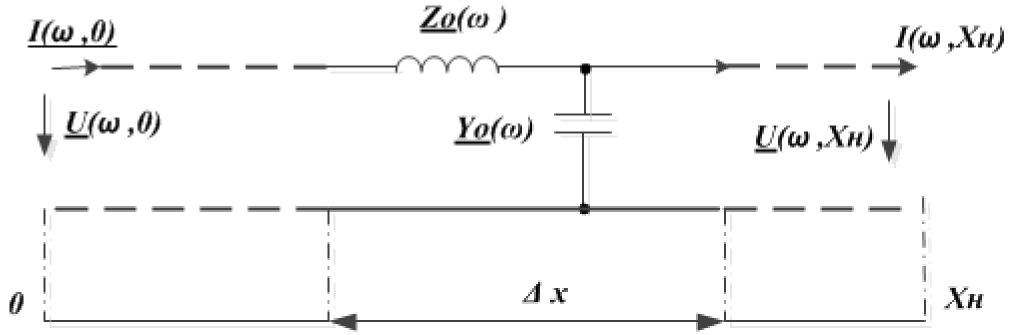
Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};\qquad L_0 = \mu \cdot \lg(\frac{2 \cdot D}{d});\qquad C_0 = \frac{\varepsilon}{\lg(\frac{2 \cdot D}{d})};$$

$$V_w = \frac{1}{\sqrt{\mu \cdot \varepsilon}};$$

Проводной канал без потерь



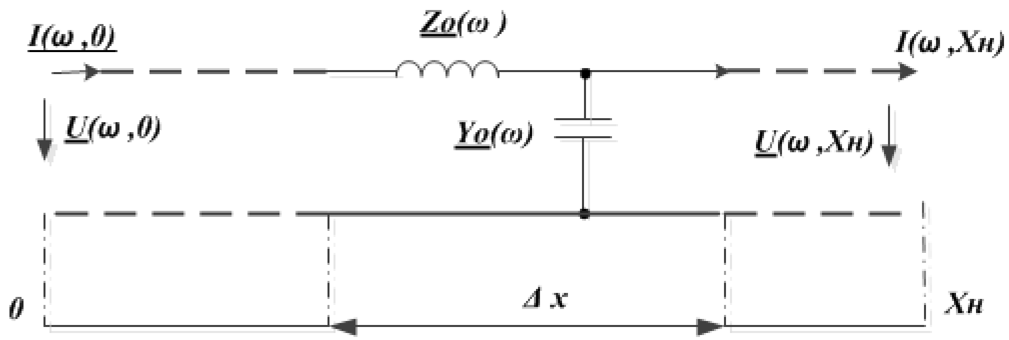
$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}}; \qquad L_0 = \mu \cdot \lg(\frac{2 \cdot D}{d}); \qquad C_0 = \frac{\varepsilon}{\lg(\frac{2 \cdot D}{d})};$$

$$V_w = \frac{1}{\sqrt{\mu \cdot \varepsilon}}; \qquad \mu = \mu_{отн} \cdot \mu_0 = \mu_{отн} \cdot 4 \cdot \pi \cdot 10^{-7} \quad \frac{Гн}{м}; \qquad \varepsilon = \varepsilon_{отн} \cdot \varepsilon_0 = \varepsilon_{отн} \cdot \frac{10^{-9}}{36 \cdot \pi} \quad \frac{Ф}{м};$$

$$V_w = \frac{1}{\sqrt{\mu_{отн} \cdot \mu_0 \cdot \varepsilon_{отн} \cdot \varepsilon_0}} = \frac{1}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \cdot \frac{1}{\sqrt{\mu_0 \cdot \varepsilon_0}} = \frac{1}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \cdot 3 \cdot 10^8 \quad \frac{м}{с};$$

$$V_w \leq V_{w0} = 3 \cdot 10^8 \quad \frac{м}{с};$$

Проводной канал без потерь



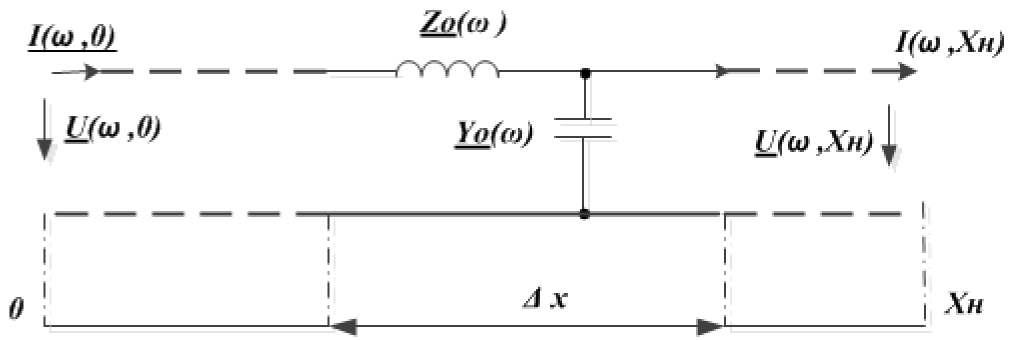
$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

$$L_0 = \mu \cdot \lg(\frac{2 \cdot D}{d}); \qquad \mathrm{C}_0 = \frac{\varepsilon}{\lg(\frac{2 \cdot D}{d})};$$

$$V_w = \frac{3 \cdot 10^8}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \quad \left\langle \frac{м}{c} \right\rangle;$$

$$\underline{\gamma_0}(\omega) = j \cdot \omega \sqrt{L_0 \cdot C_0} = j \cdot \frac{\omega}{V_w} \quad \left\langle \frac{1}{м} \right\rangle;$$

Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

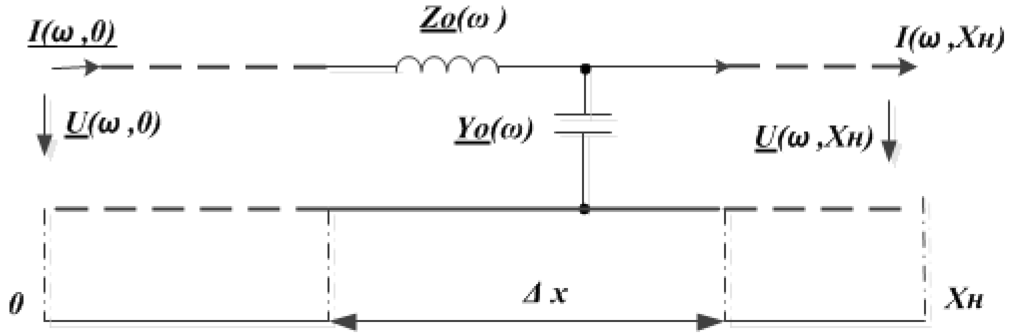
$$L_0 = \mu \cdot \lg(\frac{2 \cdot D}{d}); \qquad C_0 = \frac{\varepsilon}{\lg(\frac{2 \cdot D}{d})};$$

$$V_w = \frac{3 \cdot 10^8}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \quad \left\langle \frac{м}{c} \right\rangle;$$

$$\underline{\gamma_0}(\omega) = j \cdot \omega \sqrt{L_0 \cdot C_0} = j \cdot \frac{\omega}{V_w} \quad \left\langle \frac{1}{м} \right\rangle;$$

$$\underline{\gamma_0}(\omega) = j \cdot \frac{\omega}{V_w} = j \cdot \frac{2 \cdot \pi \cdot f}{V_w} = j \cdot \frac{2 \cdot \pi}{\lambda_w} \quad \left\langle \frac{1}{м} \right\rangle;$$

Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

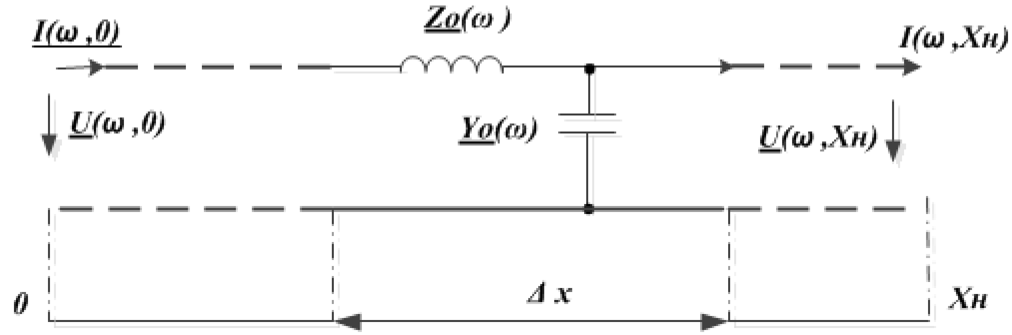
$$L_0 = \mu \cdot \lg(\frac{2 \cdot D}{d}); \qquad C_0 = \frac{\varepsilon}{\lg(\frac{2 \cdot D}{d})};$$

$$V_w = \frac{3 \cdot 10^8}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \quad \left\langle \frac{м}{c} \right\rangle;$$

$$\underline{\gamma_0}(\omega) = j \cdot \frac{\omega}{V_w} = j \cdot \frac{2 \cdot \pi \cdot f}{V_w} = j \cdot \frac{2 \cdot \pi}{\lambda_w} \quad \left\langle \frac{1}{м} \right\rangle;$$

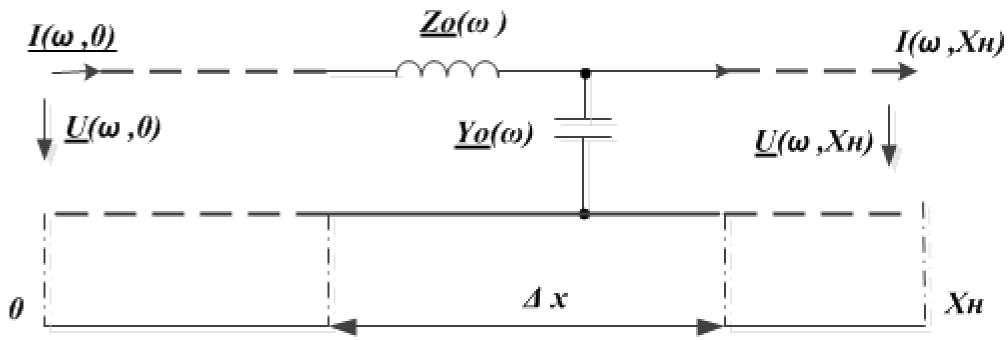
$$Z_w == \sqrt{\frac{\underline{Z_0}(\omega)}{\underline{Y_0}(\omega)}} = \sqrt{\frac{j \cdot \omega \cdot L_0}{j \cdot \omega \cdot C_0}} = \sqrt{\frac{L_0}{C_0}} = \sqrt{\frac{\mu}{\varepsilon}} \cdot \lg(\frac{2 \cdot D}{d}) \quad \langle Ом \rangle;$$

Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega,x)=\underline{U}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-Z_w\cdot\underline{I}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,x)=\underline{I}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-\dfrac{1}{Z_w}\cdot\underline{U}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

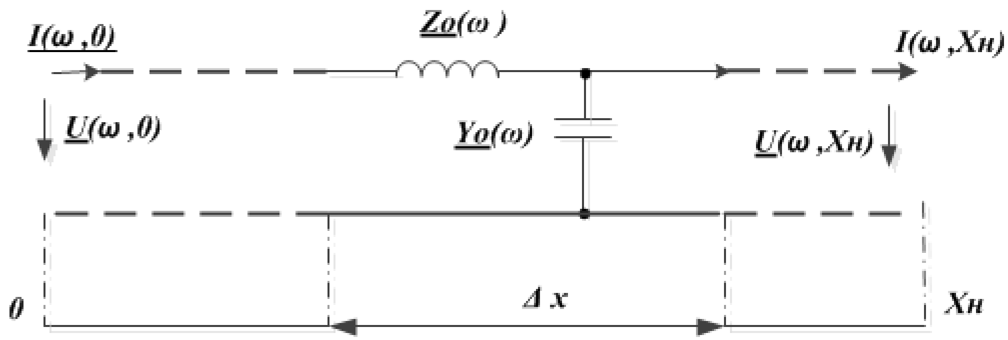
Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega,x) = \underline{U}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - Z_w\cdot \underline{I}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,x) = \underline{I}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - Z_w\cdot \underline{U}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

$$\begin{cases} ch\left[\underline{\gamma_0}(\omega)\cdot x\right] = Cos\left[\dfrac{\omega}{V_w}\cdot x\right]; \\ sh\left[\underline{\gamma_0}(\omega)\cdot x\right] = j\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \end{cases}$$

Проводной канал без потерь

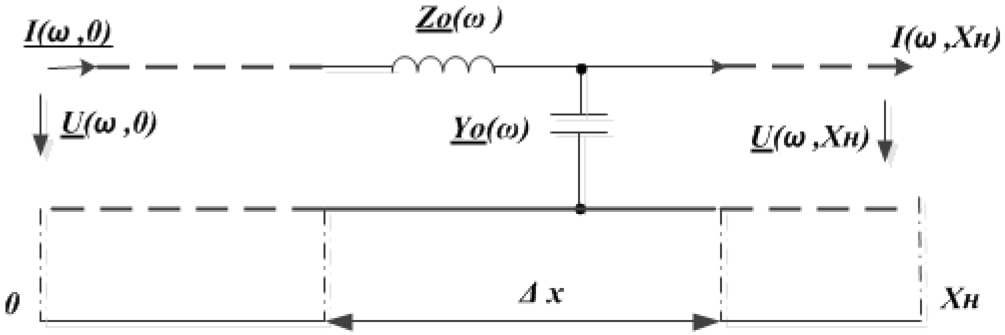


$$\begin{cases} \underline{U}(\omega,x)=\underline{U}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-Z_w\cdot\underline{I}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,x)=\underline{I}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-\dfrac{1}{Z_w}\cdot\underline{U}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

$$\begin{cases} ch\left[\underline{\gamma_0}(\omega)\cdot x\right]=Cos\left[\dfrac{\omega}{V_w}\cdot x\right]; \\ sh\left[\underline{\gamma_0}(\omega)\cdot x\right]=j\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega,x)=\underline{U}(\omega,0)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right]-j\cdot Z_w\cdot\underline{I}(\omega,0)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \\ \underline{I}(\omega,x)=\underline{I}(\omega,0)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right]-\dfrac{j}{Z_w}\cdot\underline{U}(\omega,0)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \end{cases}$$

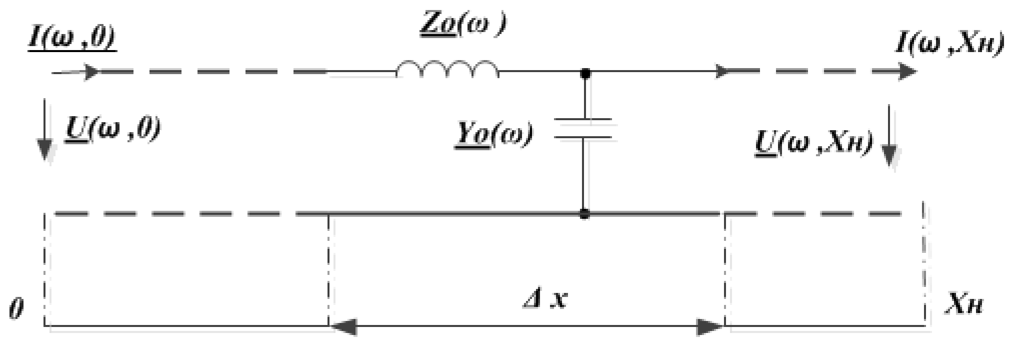
Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega,x) = \underline{U}(\omega,0)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right] - j\cdot Z_w\cdot \underline{I}(\omega,0)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \\ \underline{I}(\omega,x) = \underline{I}(\omega,0)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right] - \dfrac{j}{Z_w}\cdot \underline{U}(\omega,0)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega,0) = \underline{U}(\omega,x)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right] + j\cdot Z_w\cdot \underline{I}(\omega,0)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \\ \underline{I}(\omega,0) = \dfrac{j}{Z_w}\cdot \underline{U}(\omega,x)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right] + \underline{I}(\omega,x)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right]; \end{cases}$$

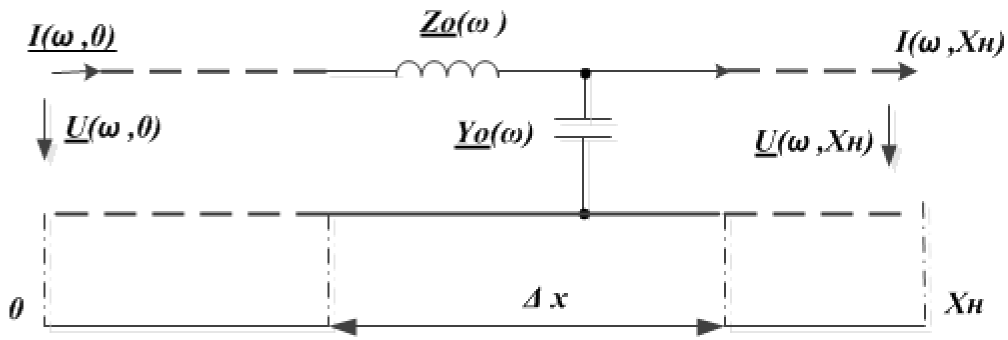
Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega,0) = \underline{U}(\omega,x)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right] + j\cdot Z_w\cdot \underline{I}(\omega,0)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]; \\ \underline{I}(\omega,0) = \dfrac{j}{Z_w}\cdot \underline{U}(\omega,x)\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right] + \underline{I}(\omega,x)\cdot Cos\left[\dfrac{\omega}{V_w}\cdot x\right]; \end{cases}$$

$$\begin{bmatrix} \underline{U}(\omega,0) \\ \underline{I}(\omega,0) \end{bmatrix} = \begin{bmatrix} Cos\left[\dfrac{\omega}{V_w}\cdot x\right] & j\cdot Z_w\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right] \\ \dfrac{j}{Z_w}\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right] & Cos\left[\dfrac{\omega}{V_w}\cdot x\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega,x) \\ \underline{I}(\omega,x) \end{bmatrix}$$

Проводной канал без потерь

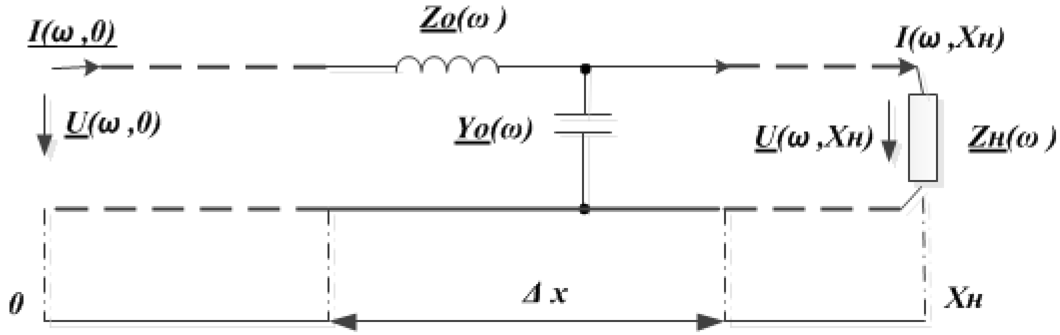


$$\begin{bmatrix} \underline{U}(\omega,0) \\ \underline{I}(\omega,0) \end{bmatrix} = \begin{bmatrix} Cos\left[\frac{\omega}{V_w}\cdot x\right] & j\cdot Z_w\cdot Sin\left[\frac{\omega}{V_w}\cdot x\right] \\ \frac{j}{Z_w}\cdot Sin\left[\frac{\omega}{V_w}\cdot x\right] & Cos\left[\frac{\omega}{V_w}\cdot x\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega,x) \\ \underline{I}(\omega,x) \end{bmatrix}$$

$$\underline{A_{11}}(\omega) = Cos\left[\frac{\omega}{V_w}\cdot x\right]; \qquad \underline{A_{12}}(\omega) = j\cdot Z_w\cdot Sin\left[\frac{\omega}{V_w}\cdot x\right];$$

$$\underline{A_{21}}(\omega) = \frac{j}{Z_w}\cdot Sin\left[\frac{\omega}{V_w}\cdot x\right]; \qquad \underline{A_{22}}(\omega) = Cos\left[\frac{\omega}{V_w}\cdot x\right];$$

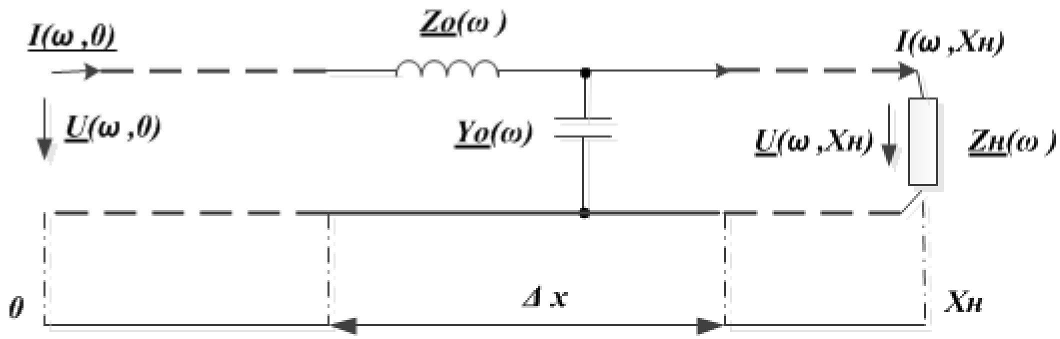
Проводной канал без потерь



$$\begin{bmatrix} \underline{U}(\omega,0) \\ \underline{I}(\omega,0) \end{bmatrix} = \begin{bmatrix} Cos\left[\frac{\omega}{V_w}\cdot x\right] & j\cdot Z_w \cdot Sin\left[\frac{\omega}{V_w}\cdot x\right] \\ \frac{j}{Z_w}\cdot Sin\left[\frac{\omega}{V_w}\cdot x\right] & Cos\left[\frac{\omega}{V_w}\cdot x\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega,x) \\ \underline{I}(\omega,x) \end{bmatrix}$$

$$\underline{Z_H}(\omega) = \frac{\underline{U}(\omega, X_H)}{\underline{I}(\omega, X_H)};$$

Проводной канал без потерь



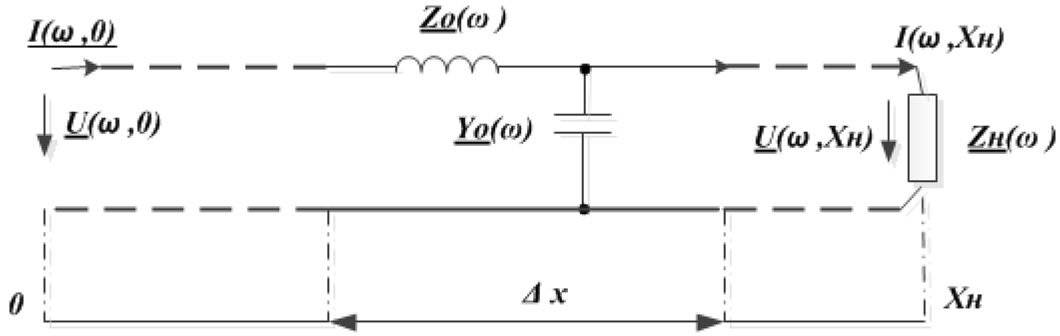
$$\begin{bmatrix}\underline{U}(\omega,0)\\ \underline{I}(\omega,0)\end{bmatrix}=\begin{bmatrix}Cos\left[\dfrac{\omega}{V_w}\cdot x\right] & j\cdot Z_w\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right]\\ \dfrac{j}{Z_w}\cdot Sin\left[\dfrac{\omega}{V_w}\cdot x\right] & Cos\left[\dfrac{\omega}{V_w}\cdot x\right]\end{bmatrix}\cdot\begin{bmatrix}\underline{U}(\omega,x)\\ \underline{I}(\omega,x)\end{bmatrix}$$

$$\underline{Z}_H(\omega)=\frac{\underline{U}(\omega,X_H)}{\underline{I}(\omega,X_H)};$$

$$\underline{U}(\omega,0)=\left[Cos\left(\frac{\omega}{V_w}\cdot X_H\right)+j\cdot\frac{Z_w}{\underline{Z}_H(\omega)}\cdot Sin\left(\frac{\omega}{V_w}\cdot X_H\right)\right]\cdot\underline{U}(\omega,X_H);$$

$$\underline{I}(\omega,0)=\left[Cos\left(\frac{\omega}{V_w}\cdot X_H\right)+j\cdot\frac{\underline{Z}_H(\omega)}{Z_w}\cdot Sin\left(\frac{\omega}{V_w}\cdot X_H\right)\right]\cdot\underline{I}(\omega,X_H);$$

Проводной канал без потерь



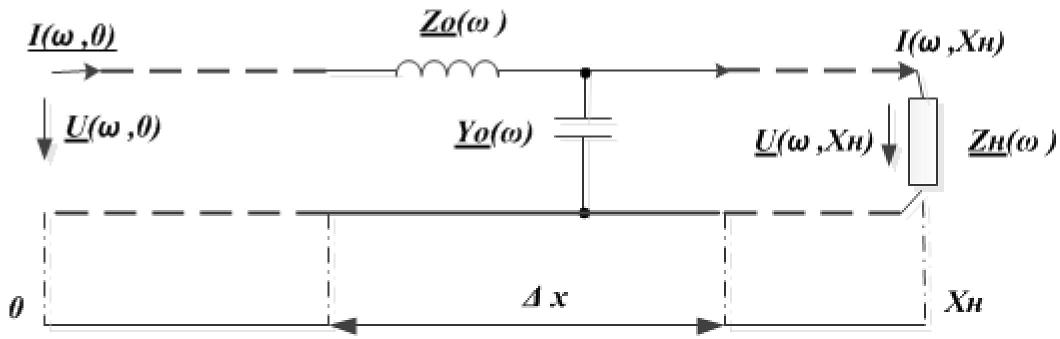
$$\underline{U}(\omega,0)=\left[Cos(\frac{\omega}{V_w}\cdot X_H)+j\cdot\frac{Z_w}{\underline{Z_H}(\omega)}\cdot Sin(\frac{\omega}{V_w}\cdot X_H)\right]\cdot\underline{U}(\omega,X_H);$$

$$\underline{I}(\omega,0)=\left[Cos(\frac{\omega}{V_w}\cdot X_H)+j\cdot\frac{\underline{Z_H}(\omega)}{Z_w}\cdot Sin(\frac{\omega}{V_w}\cdot X_H)\right]\cdot\underline{I}(\omega,X_H);$$

$$\underline{U}(\omega,X_H)=\left[Cos(\frac{\omega}{V_w}\cdot X_H)-j\cdot\frac{Z_w}{\underline{Z_H}(\omega)}\cdot Sin(\frac{\omega}{V_w}\cdot X_H)\right]\cdot\underline{U}(\omega,0);$$

$$\underline{I}(\omega,X_H)=\left[Cos(\frac{\omega}{V_w}\cdot X_H)-j\cdot\frac{\underline{Z_H}(\omega)}{Z_w}\cdot Sin(\frac{\omega}{V_w}\cdot X_H)\right]\cdot\underline{I}(\omega,0);$$

Проводной канал без потерь



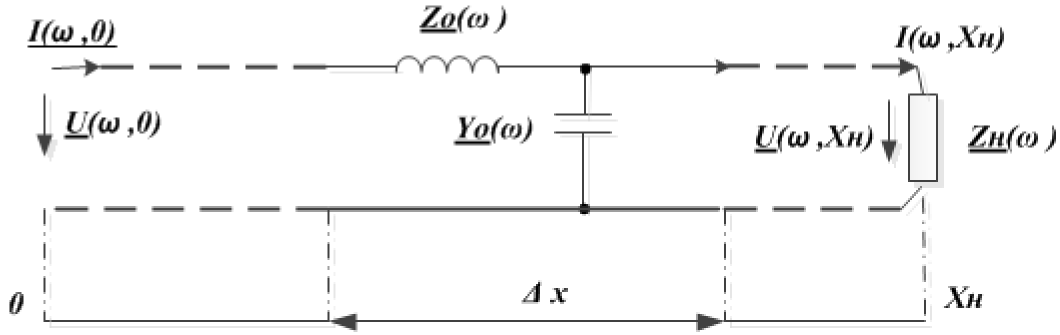
$$\underline{U}(\omega, X_H) = \left[Cos(\frac{\omega}{V_w} \cdot X_H) - j \cdot \frac{Z_w}{\underline{Z}_H(\omega)} \cdot Sin(\frac{\omega}{V_w} \cdot X_H) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\frac{\omega}{V_w} \cdot X_H) - j \cdot \frac{\underline{\underline{Z}}_H(\omega)}{Z_w} \cdot Sin(\frac{\omega}{V_w} \cdot X_H) \right] \cdot \underline{I}(\omega, 0);$$

$$\frac{\omega}{V_w} \cdot X_H = \omega \cdot \tau_p$$

τ_p - время распрстранения ЭМК

Проводной канал без потерь



$$\underline{U}(\omega, X_H) = \left[Cos(\frac{\omega}{V_w} \cdot X_H) - j \cdot \frac{Z_w}{\underline{Z}_H(\omega)} \cdot Sin(\frac{\omega}{V_w} \cdot X_H) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\frac{\omega}{V_w} \cdot X_H) - j \cdot \frac{\underline{Z}_H(\omega)}{Z_w} \cdot Sin(\frac{\omega}{V_w} \cdot X_H) \right] \cdot \underline{I}(\omega, 0);$$

$$\frac{\omega}{V_w} \cdot X_H = \omega \cdot \tau_p$$

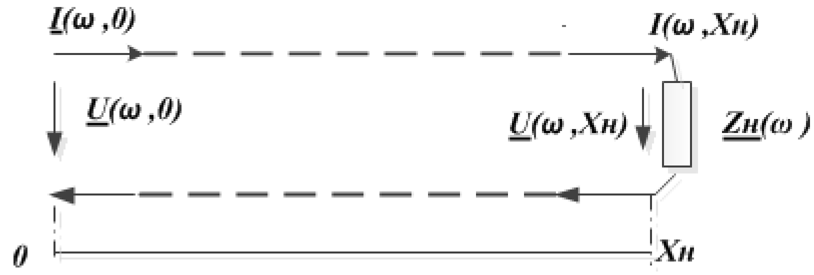
τ_p - время распрстранения ЭМК

$$\underline{U}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot \frac{Z_w}{\underline{Z}_H(\omega)} \cdot Sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot \frac{\underline{Z}_H(\omega)}{Z_w} \cdot Sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot \frac{\underline{Z}_w(\omega)}{\underline{Z}_H(\omega)} \cdot Sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot \frac{\underline{Z}_H(\omega)}{\underline{Z}_w(\omega)} \cdot Sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

$$\frac{\omega}{V_w} \cdot X_H = \omega \cdot \tau_p$$

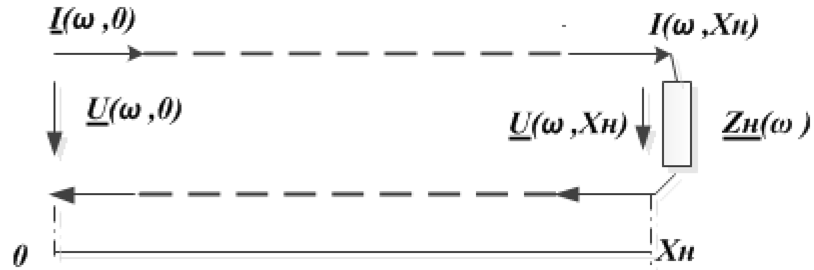
τ_p - время распрстранения ЭМК

$$\underline{U}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot\frac{\underline{Z}_w(\omega)}{\underline{Z}_H(\omega)}\cdot Sin(\omega\cdot\tau_p) \right]\cdot\underline{U}(\omega,0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot\frac{\underline{Z}_H(\omega)}{\underline{Z}_w(\omega)}\cdot Sin(\omega\cdot\tau_p) \right]\cdot\underline{I}(\omega,0);$$

$$\frac{\omega}{V_w}\cdot X_H = \omega\cdot\tau_p$$

τ_p - время распрстранения ЭМК

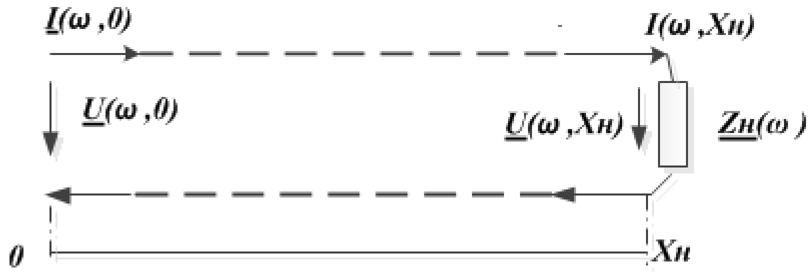
$$\underline{U}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p) \right]\cdot\underline{U}(\omega,0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p) \right]\cdot\underline{I}(\omega,0);$$

$$\underline{Z}_{вх}(\omega) = \frac{\underline{U}(\omega,0)}{\underline{I}(\omega,0)} = \frac{\underline{U}(\omega,X_H)}{\underline{I}(\omega,X_H)} = Z_w;$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



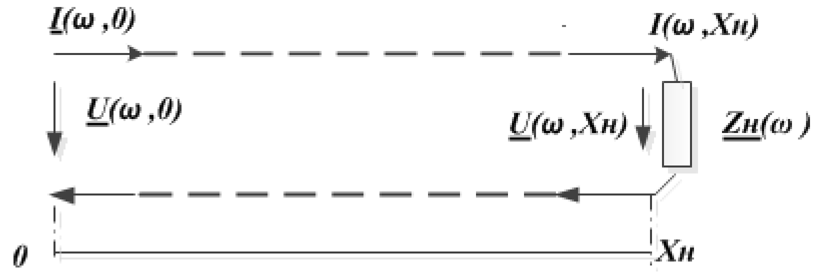
$$\underline{U}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p)\right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p)\right] \cdot \underline{I}(\omega, 0);$$

$$Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p)\right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p)\right] \cdot \underline{I}(\omega, 0);$$

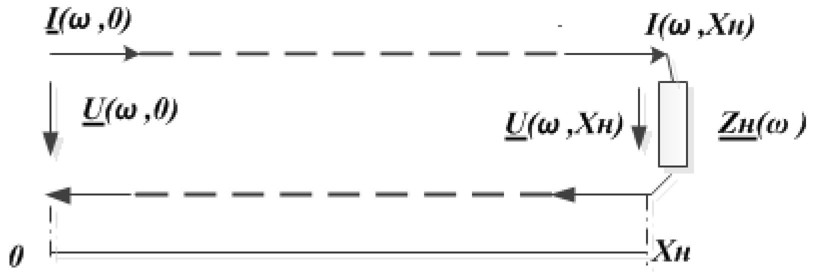
$$Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p)\right]\cdot\underline{U}(\omega,0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p)\right]\cdot\underline{I}(\omega,0);$$

$$Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p) = e^{-j\cdot\omega\cdot\tau_p};$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega,0)\cdot e^{-j\cdot\omega\cdot\tau_p};$$

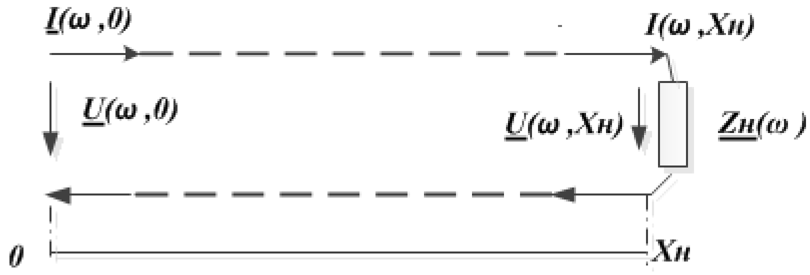
$$\underline{I}(\omega, X_H) = \underline{I}(\omega,0)\cdot e^{-j\cdot\omega\cdot\tau_p};$$

$$\underline{T_u}(\omega, X_H) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega,0)} = e^{-j\cdot\omega\cdot\tau_p};$$

$$\underline{T_i}(\omega, X_H) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega,0)} = e^{-j\cdot\omega\cdot\tau_p};$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p)\right]\cdot\underline{U}(\omega,0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p)\right]\cdot\underline{I}(\omega,0);$$

$$Cos(\omega\cdot\tau_p) - j\cdot Sin(\omega\cdot\tau_p) = e^{-j\cdot\omega\cdot\tau_p};$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega,0)\cdot e^{-j\cdot\omega\cdot\tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega,0)\cdot e^{-j\cdot\omega\cdot\tau_p};$$

$$\underline{T}_u(\omega, X_H) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega,0)} = e^{-j\cdot\omega\cdot\tau_p};$$

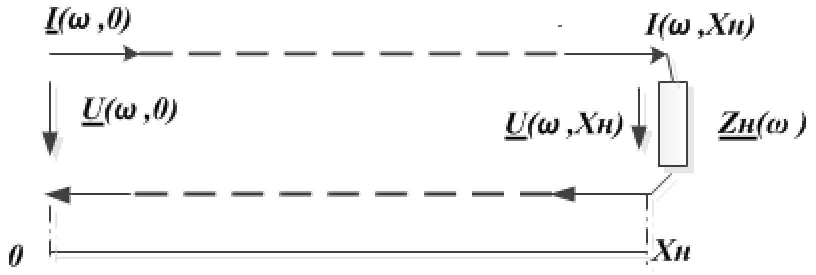
$$\underline{T}_i(\omega, X_H) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega,0)} = e^{-j\cdot\omega\cdot\tau_p};$$

$$u(t, X_H) = u(t-\tau_p, 0);$$

$$i(t, X_H) = i(t-\tau_p, 0);$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p)\right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p)\right] \cdot \underline{I}(\omega, 0);$$

$$Cos(\omega \cdot \tau_p) - j \cdot Sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{T}_u(\omega, X_H) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$

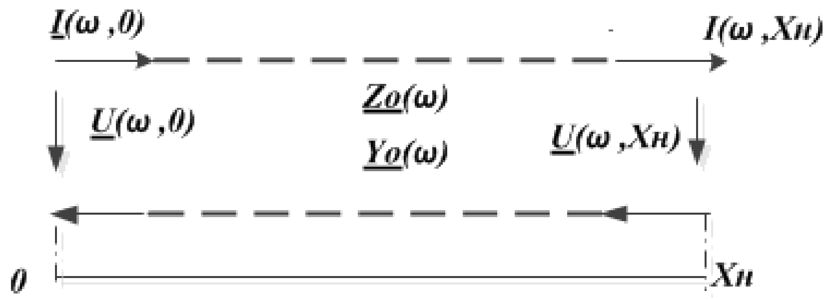
$$\underline{T}_i(\omega, X_H) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$

$$u(t, X_H) = u(t - \tau_p, 0);$$

$$i(t, X_H) = i(t - \tau_p, 0);$$

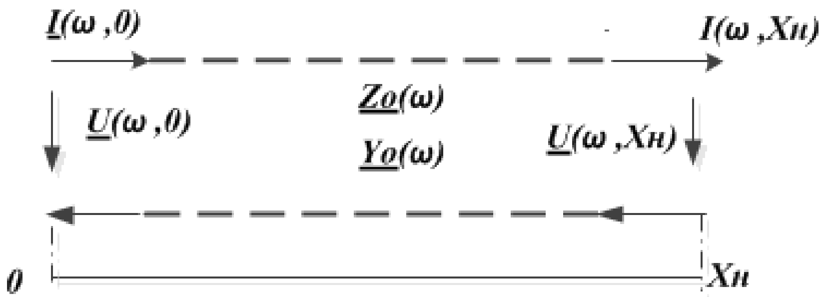
$$p(t, X_H) = p(t - \tau_p, 0);$$

Проводной канал с малыми потерями



$$\omega \cdot L_0 >> R_0; \qquad \omega \cdot C_0 >> G_0;$$

Проводной канал с малыми потерями



$$\omega \cdot L_0 >> R_0; \qquad \omega \cdot C_0 >> G_0;$$

$$\underline{\gamma_0}^2(\omega) = \underline{Z_0}(\omega) \cdot \underline{Y_0}(\omega) = (j \cdot \omega \cdot L_0 + R_0) \cdot (j \cdot \omega \cdot C_0 + G_0) =$$

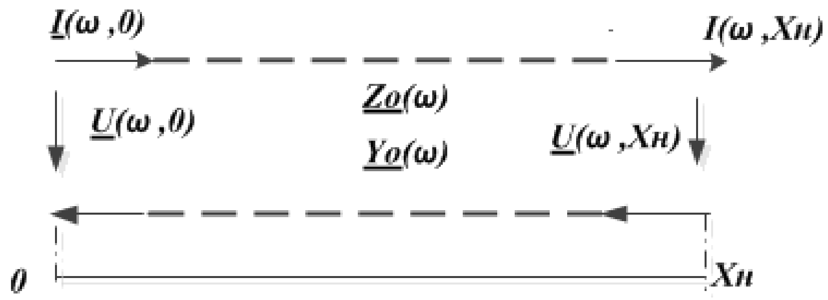
$$= j \cdot \omega \cdot L_0 \cdot (1 + \frac{R_0}{j \cdot \omega \cdot L_0}) \cdot j \cdot \omega \cdot C_0 \cdot (1 + \frac{G_0}{j \cdot \omega \cdot C_0}) =$$

$$= -\omega^2 \cdot L_0 \cdot C_0 \cdot (1 - j \cdot \frac{R_0}{\omega \cdot L_0}) \cdot (1 - j \cdot \frac{G_0}{\omega \cdot C_0}) =$$

$$-\omega^2 \cdot L_0 \cdot C_0 \cdot \left[\left(1 + \frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) - j \cdot \left(\frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right] \approx$$

$$\approx \omega^2 \cdot L_0 \cdot C_0 \cdot \left[-1 + j \cdot \left(\frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right];$$

Проводной канал с малыми потерями

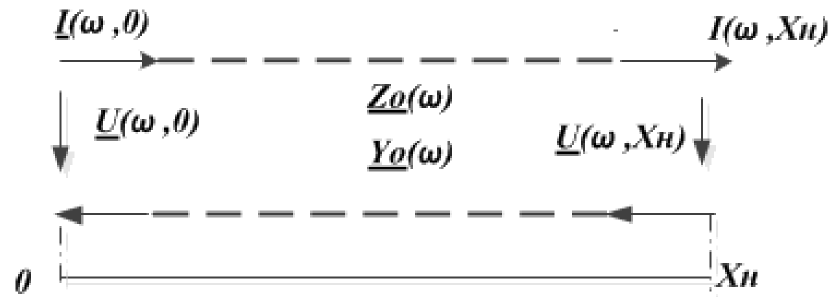


$$\omega \cdot L_0 >> R_0; \qquad \omega \cdot C_0 >> G_0;$$

$$\underline{\gamma_0}^2(\omega) = \underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega) \approx \omega^2 \cdot L_0 \cdot C_0 \cdot \left[-1 + j \cdot \left(\frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right];$$

$$V_0 = \frac{1}{\sqrt{L_0 \cdot C_0}} \quad \text{м/с};$$

Проводной канал с малыми потерями



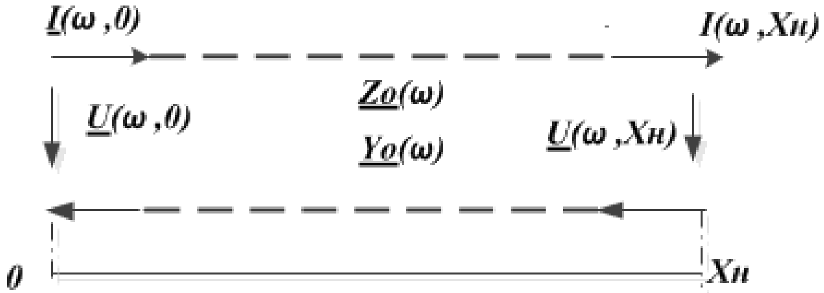
$$\omega \cdot L_0 >> R_0; \qquad \omega \cdot C_0 >> G_0;$$

$$\underline{\gamma_0}^2(\omega) = \underline{Z_0}(\omega) \cdot \underline{Y_0}(\omega) \approx \omega^2 \cdot L_0 \cdot C_0 \cdot \left[-1 + j \cdot \left(\frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right];$$

$$V_0 = \frac{1}{\sqrt{L_0 \cdot C_0}} \text{ м/с};$$

$$\mathrm{tg}(\delta_\omega) = \frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0}$$

Проводной канал с малыми потерями

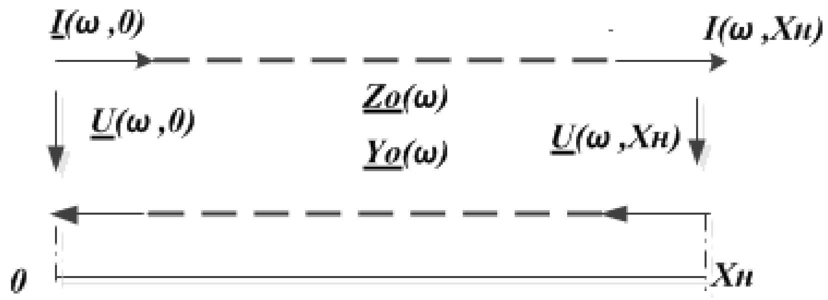


$$\underline{\gamma_0}^2(\omega) = \frac{\omega^2}{V_0^2} \cdot \left[-1 + j \cdot \operatorname{tg}(\delta_\omega)\right] =$$

$$= -\frac{\omega^2}{V_0^2} \cdot \frac{\cos(\delta_\omega) - j \cdot \sin(\delta_\omega)}{\cos(\delta_\omega)} =$$

$$= -\frac{\omega^2}{V_0^2} \cdot \frac{e^{-j \cdot \delta_\omega}}{\cos(\delta_\omega)}$$

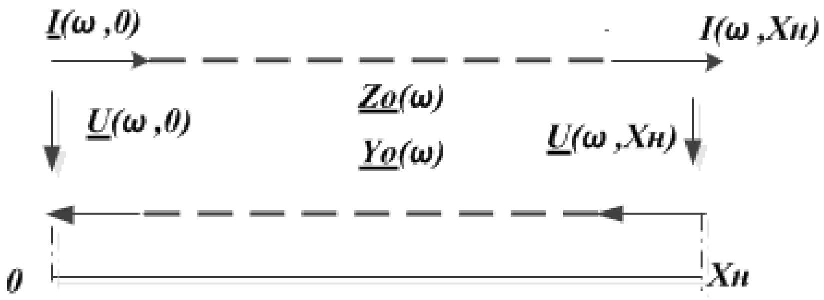
Проводной канал с малыми потерями



$$\underline{\gamma_0}^2(\omega) = \frac{\omega^2}{V_o^2} \cdot \frac{e^{j\cdot(\pi-\delta_\omega)}}{\cos(\delta_\omega)} = -\frac{\omega^2}{V_o^2} \cdot \frac{e^{-j\cdot\delta_\omega}}{\cos(\delta_\omega)};$$

$$\underline{\gamma_0}(\omega) = j \cdot \frac{\omega}{V_0} \cdot e^{-j\cdot\frac{\delta_\omega}{2}} \sqrt{\frac{1}{\cos(\delta_\omega)}} = \frac{\omega}{V_0 \cdot \sqrt{cos(\delta_\omega)}} \left[\sin(\frac{\delta_\omega}{2}) + j \cdot \cos(\frac{\delta_\omega}{2}) \right];$$

Проводной канал с малыми потерями



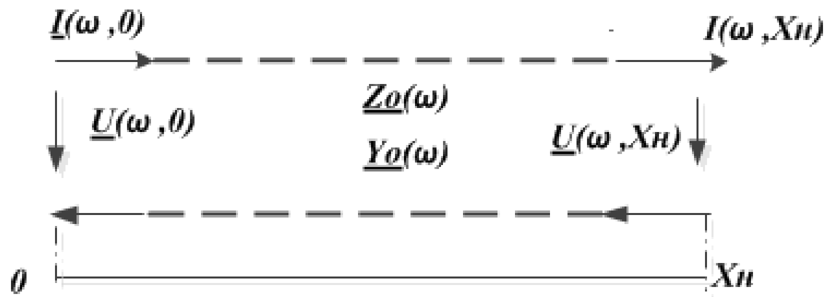
$$\underline{\gamma}_0(\omega) = j \cdot \frac{\omega}{V_0} \cdot e^{-j \cdot \frac{\delta_\omega}{2}} \sqrt{\frac{1}{\cos(\delta_\omega)}} = \frac{\omega}{V_0 \cdot \sqrt{cos(\delta_\omega)}} \left[\sin(\frac{\delta_\omega}{2}) + j \cdot \cos(\frac{\delta_\omega}{2}) \right];$$

$$\underline{\gamma}_0(\omega) = \alpha_0(\omega) + j \cdot \beta_0(\omega);$$

$$\alpha_0(\omega) = \frac{\omega \cdot \sin(\frac{\delta_\omega}{2})}{V_0 \cdot \sqrt{cos(\delta_\omega)}};$$

$$\beta_0(\omega) = \frac{\omega \cdot \cos(\frac{\delta_\omega}{2})}{V_0 \cdot \sqrt{cos(\delta_\omega)}};$$

Проводной канал с малыми потерями



$$\omega \cdot L_0 >> R_0; \qquad \omega \cdot C_0 >> G_0;$$

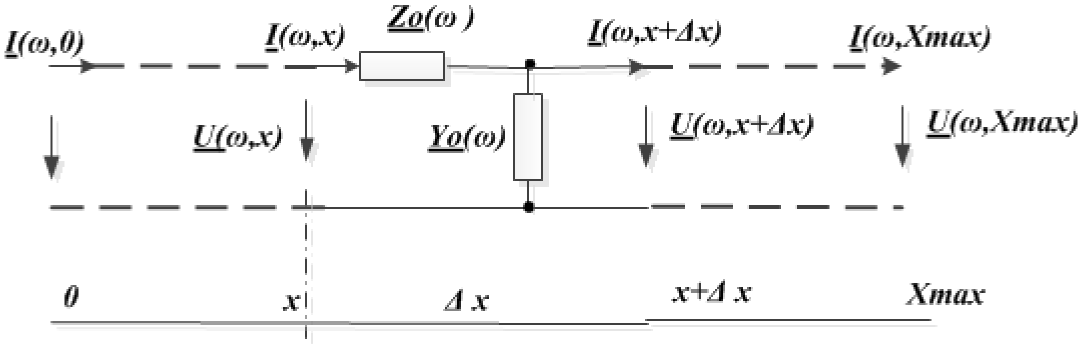
$$\underline{Z}_w(\omega) = \sqrt{\frac{\underline{Z}_0(\omega)}{\underline{Y}_0(\omega)}}$$

$$\underline{Z}_0(\omega) = \left[j \cdot \omega \cdot L_0 + R_0 \right];$$

$$\underline{Y}_0(\omega) = \left[j \cdot \omega \cdot C_0 + G_0 \right];$$

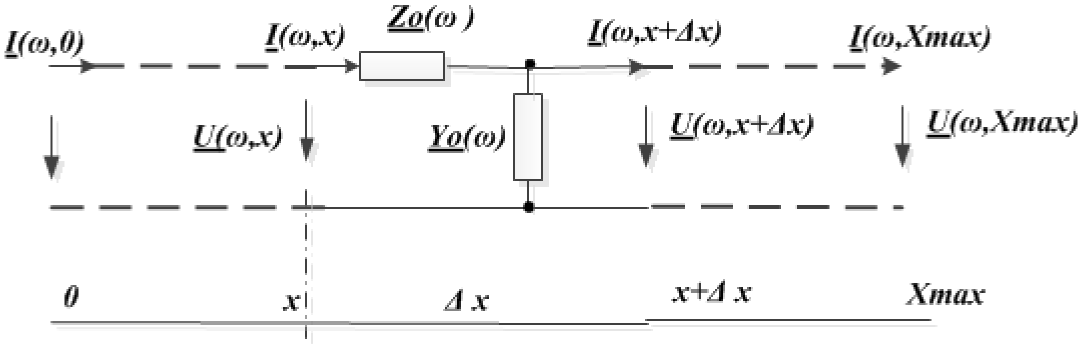
$$\underline{Z}_w(\omega) = \sqrt{\frac{L_0}{C_0}} \cdot \sqrt{\frac{1 - j \cdot \dfrac{R_0}{\omega \cdot L_0}}{1 - j \cdot \dfrac{G_0}{\omega \cdot C_0}}} \approx \sqrt{\frac{L_0}{C_0}} = Z_w$$

Проводной канал с малыми потерями



$$\begin{cases} \underline{U}(\omega,x) = \underline{U}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - Z_w\cdot \underline{I}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,x) = \underline{I}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right] - \dfrac{1}{Z_w}\cdot \underline{U}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

Проводной канал с малыми потерями

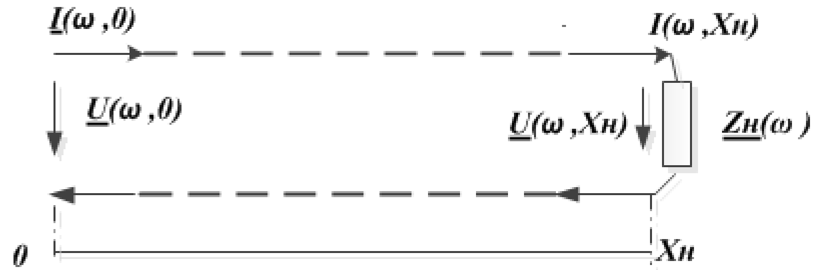


$$\begin{cases} \underline{U}(\omega,x)=\underline{U}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-Z_w\cdot\underline{I}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \\ \underline{I}(\omega,x)=\underline{I}(\omega,0)\cdot ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-\frac{1}{Z_w}\cdot\underline{U}(\omega,0)\cdot sh\left[\underline{\gamma_0}(\omega)\cdot x\right]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega,x)=\underline{U}(\omega,0)\cdot\left\{ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-sh\left[\underline{\gamma_0}(\omega)\cdot x\right]\right\}; \\ \underline{I}(\omega,x)=\underline{I}(\omega,0)\cdot\left\{ch\left[\underline{\gamma_0}(\omega)\cdot x\right]-sh\left[\underline{\gamma_0}(\omega)\cdot x\right]\right\}; \end{cases}$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$

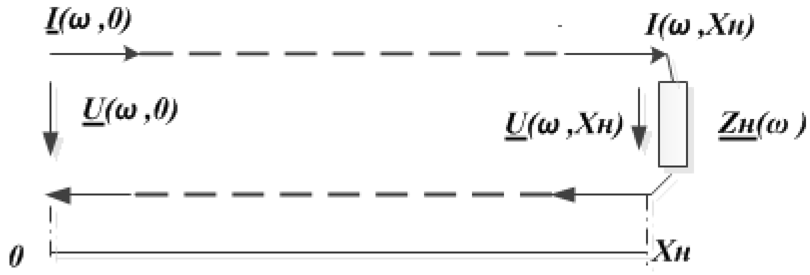


$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot \left\{ ch\left[\underline{\gamma}_0(\omega) \cdot x \right] - sh\left[\underline{\gamma}_0(\omega) \cdot x \right] \right\}; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot \left\{ ch\left[\underline{\gamma}_0(\omega) \cdot x \right] - sh\left[\underline{\gamma}_0(\omega) \cdot x \right] \right\}; \end{cases}$$

$$ch(x) - sh(x) = \frac{e^x + e^{-x}}{2} - \frac{e^x - e^{-x}}{2} = e^{-x}$$

Согласованная нагрузка

$$\underline{Z_H}(\omega) = Z_w$$



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot \left\{ ch\left[\underline{\gamma_0}(\omega) \cdot x\right] - sh\left[\underline{\gamma_0}(\omega) \cdot x\right] \right\}; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot \left\{ ch\left[\underline{\gamma_0}(\omega) \cdot x\right] - sh\left[\underline{\gamma_0}(\omega) \cdot x\right] \right\}; \end{cases}$$

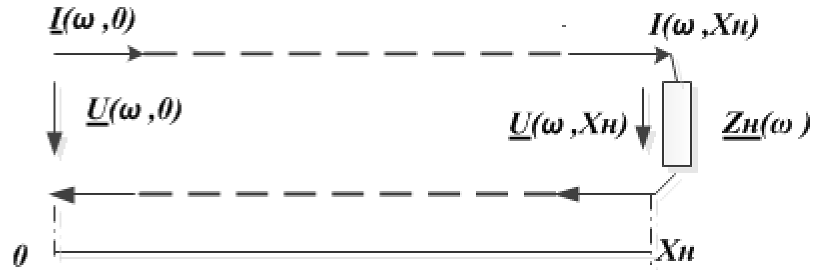
$$ch(x) - sh(x) = \frac{e^x + e^{-x}}{2} - \frac{e^x - e^{-x}}{2} = e^{-x}$$

$$\underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot x} \cdot e^{-j \cdot \beta(\omega) \cdot x};$$

$$\underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot x} \cdot e^{-j \cdot \beta(\omega) \cdot x};$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot \left\{ ch\left[\underline{\gamma}_0(\omega) \cdot x\right] - sh\left[\underline{\gamma}_0(\omega) \cdot x\right] \right\}; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot \left\{ ch\left[\underline{\gamma}_0(\omega) \cdot x\right] - sh\left[\underline{\gamma}_0(\omega) \cdot x\right] \right\}; \end{cases}$$

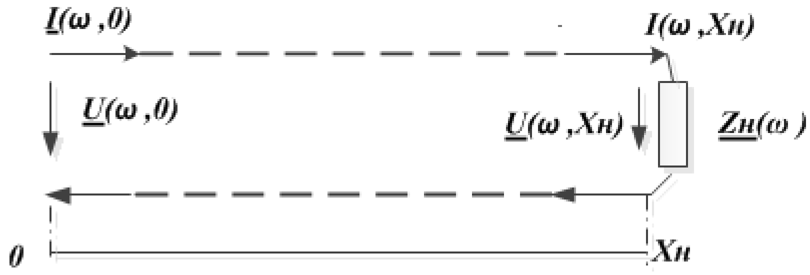
$$x = X_H$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \underline{U}(\omega,0) \cdot e^{-\alpha(\omega)\cdot X_H} \cdot e^{-j\cdot\beta(\omega)\cdot X_H};$$

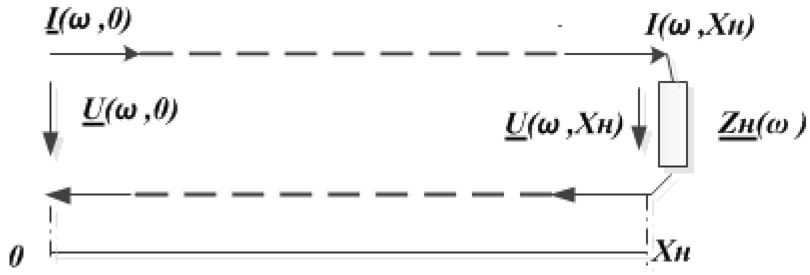
$$\underline{I}(\omega, X_H) = \underline{I}(\omega,0) \cdot e^{-\alpha(\omega)\cdot X_H} \cdot e^{-j\cdot\beta(\omega)\cdot X_H};$$

$$\underline{T}_u(\omega, X_H) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega,0)} = e^{-\alpha(\omega)\cdot X_H} \cdot e^{-j\cdot\beta(\omega)\cdot X_H};$$

$$\underline{T}_i(\omega, X_H) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega,0)} = e^{-\alpha(\omega)\cdot X_H} \cdot e^{-j\cdot\beta(\omega)\cdot X_H};$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{T}_u(\omega, X_H) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega, 0)} = e^{-\alpha(\omega)\cdot X_H} \cdot e^{-j\cdot\beta(\omega)\cdot X_H};$$

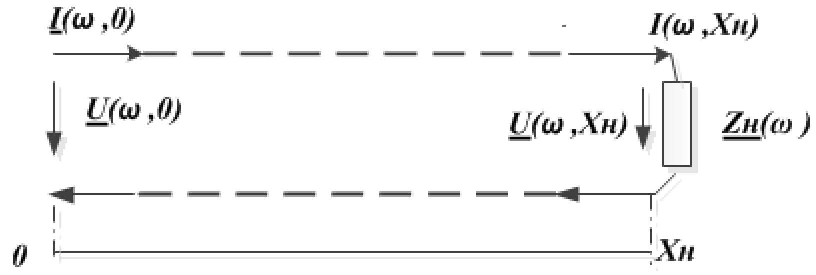
$$\underline{T}_i(\omega, X_H) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega, 0)} = e^{-\alpha(\omega)\cdot X_H} \cdot e^{-j\cdot\beta(\omega)\cdot X_H};$$

$$T_u(\omega, X_H) = \left|\underline{T}_u(\omega, X_H)\right| = e^{-\alpha(\omega)\cdot X_H}; \qquad \varphi_T = -\beta(\omega)\cdot X_H \quad \langle рад \rangle;$$

$$T_i(\omega, X_H) = \left|\underline{T}_i(\omega, X_H)\right| = e^{-\alpha(\omega)\cdot X_H}; \qquad \varphi_T = -\beta(\omega)\cdot X_H \quad \langle рад \rangle;$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$

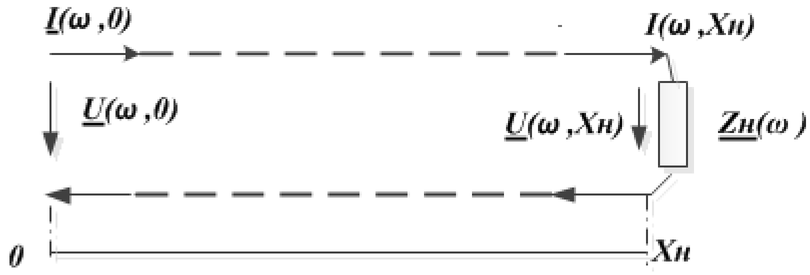


$$T_P(\omega, X_H) = T_u(\omega, X_H) \cdot T_i(\omega, X_H) = e^{-2\cdot\alpha(\omega)\cdot X_H};$$

$$LP(\omega, X_H) = 10 \cdot \lg\left[T_P(\omega, X_H)\right] =$$
$$= -20 \cdot \lg(e) \cdot \alpha(\omega) \cdot X_H =$$
$$= -8.86 \cdot \alpha(\omega) \cdot X_H \qquad \langle \partial Бм \rangle;$$

Согласованная нагрузка

$$\underline{Z}_{H}(\omega) = Z_w$$

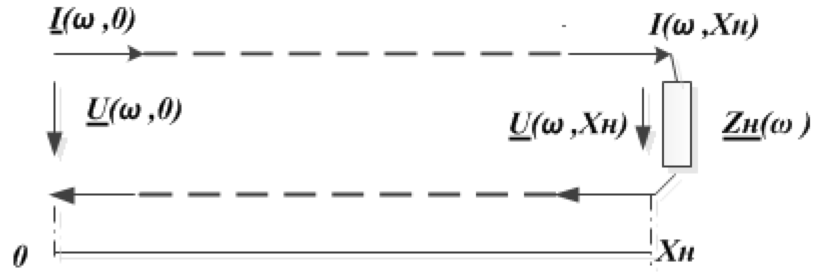


$$\delta_\omega \to 0; \quad cos(\delta_\omega) \to 1; \quad \sin(\frac{\delta_\omega}{2}) \to \frac{\delta_\omega}{2};$$

$$\alpha_0(\omega) = \frac{\omega \cdot \sin(\frac{\delta_\omega}{2})}{V_0 \cdot \sqrt{cos(\delta_\omega)}} \approx \frac{2 \cdot \pi \cdot f}{V_0} \cdot \frac{\delta_\omega}{2} = \frac{\pi}{\lambda} \cdot \delta_\omega = \alpha_0(\lambda)$$

Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



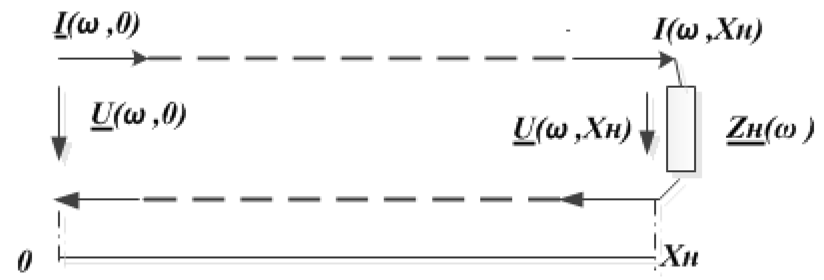
$$LP(\omega, X_H) = -8.86 \cdot \alpha(\omega) \cdot X_H \qquad \langle \partial Бм \rangle;$$

$$LP(\lambda, X_H) = 10 \cdot \lg\left[T_P(\lambda, X_H)\right] =$$

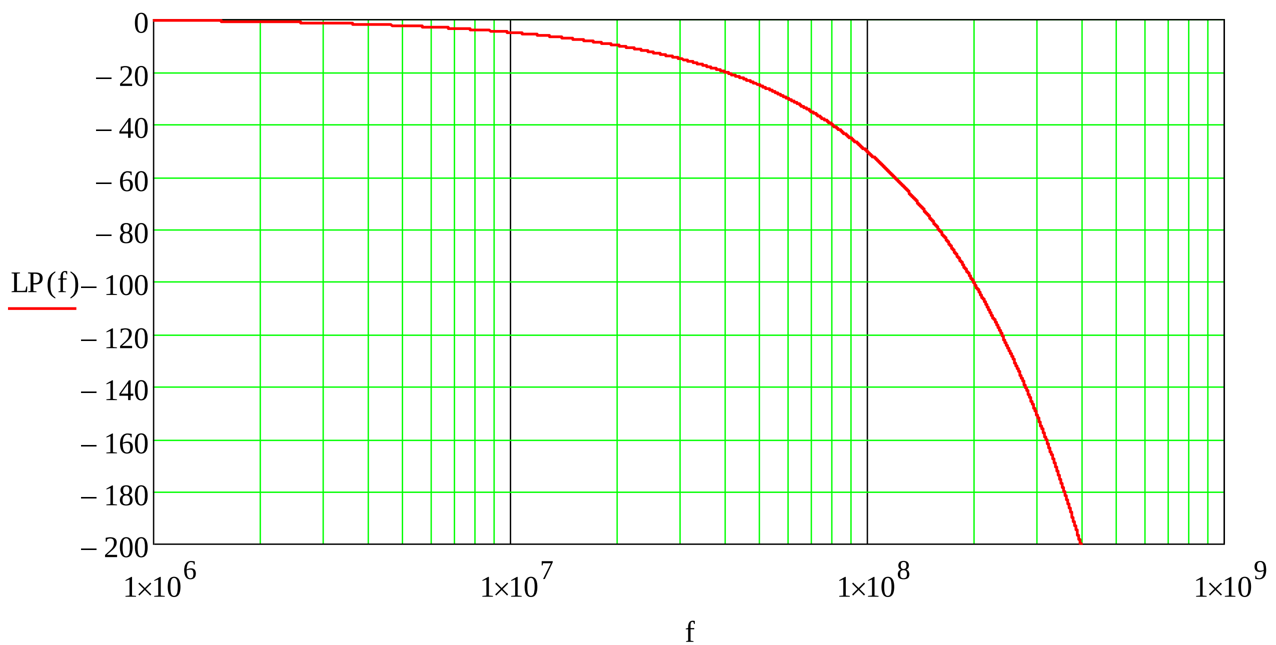
$$= -20 \cdot \lg(e) \cdot \alpha(\lambda) \cdot X_H =$$

$$= -8.86 \cdot \frac{\pi}{\lambda} \cdot \delta_\omega \cdot X_H = -27{,}8 \cdot \delta_\omega \frac{X_H}{\lambda} \qquad \langle \partial Бм \rangle;$$

Пример расчёта потери мощности



Тип кабеля: ***РК50-06-11*** $Z_w = 50\ \text{Ом};\quad X_H = 100\ м;\quad \delta_w = 0,02$



Спасибо за внимание.