Заземјувачи и заземјувачки системи во електроенергетските мрежи

Електроенергетски кабли во заземјувачкиот систем

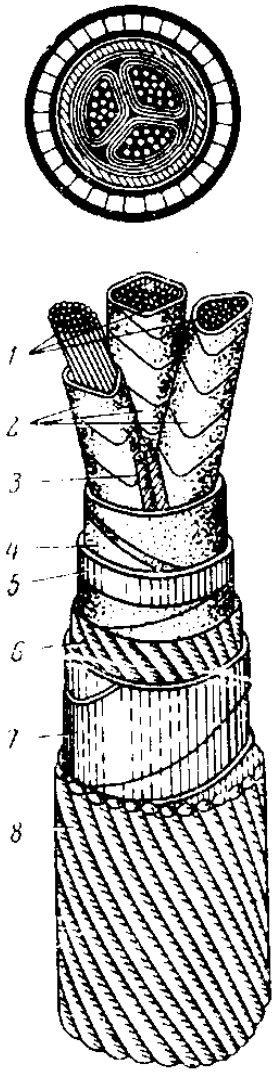
М. Тодоровски

Институт за преносни електроенергетски системи
Факултет за електротехника и информациски технологии
Универзитет Св. Кирил и Методиј

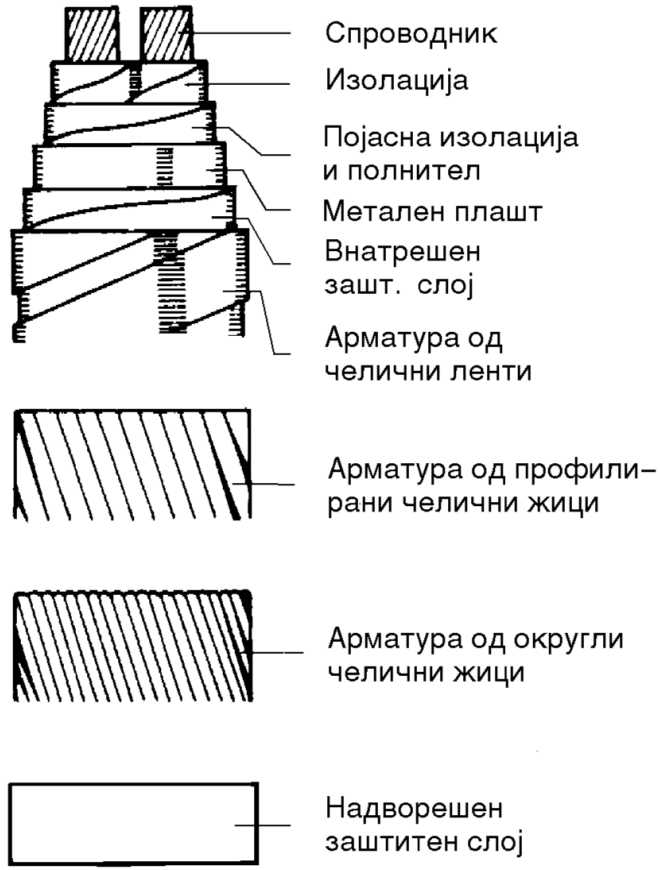
mirko@feit.ukim.edu.mk
pees.feit.ukim.edu.mk

Скопје, 2017

Општо за електроенергетските кабли

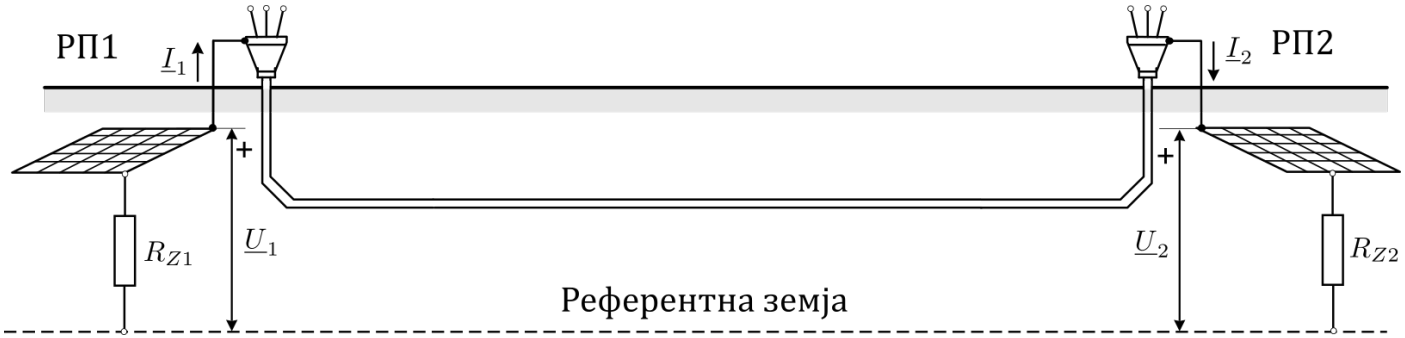


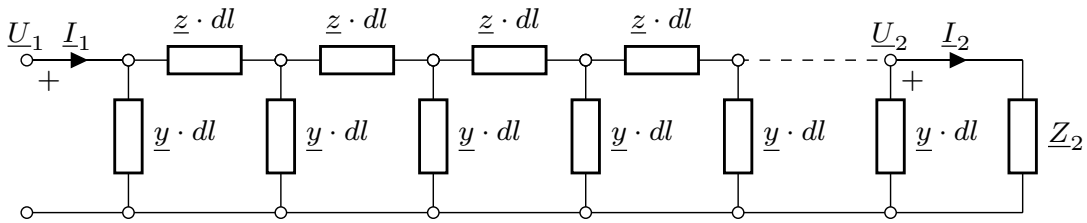
а) појасен кабел – IPO 13



б) класичен кабел

Кабли со неизолиран метален плашт





$$R_Z = \frac{\rho}{\pi \cdot l} \cdot \ln \frac{l}{\sqrt{h \cdot d_k}},$$

$$\underline{Y}_Z = \frac{1}{R_Z} = \frac{\pi \cdot l}{\rho \cdot \ln \dfrac{l}{\sqrt{h \cdot d_k}}},$$

$$\underline{y} = g + jb = \frac{\underline{Y}_Z}{l} = \frac{\pi}{\rho \cdot \ln \dfrac{l}{\sqrt{h \cdot d_k}}}.$$

Кабли со неизолиран метален плашт

$$\underline{U}_1 = \underline{U}_2 \cdot \mathrm{ch}\underline{\gamma} l + \underline{Z}_C \cdot \underline{I}_2 \cdot \mathrm{sh}\underline{\gamma} l,$$
$$\underline{I}_1 = \frac{\underline{U}_2}{\underline{Z}_C} \cdot \mathrm{sh}\underline{\gamma} l + \underline{I}_2 \cdot \mathrm{ch}\underline{\gamma} l.$$

$$\underline{\gamma} = \sqrt{\underline{z} \cdot \underline{y}} = \sqrt{(r + jx) \cdot g} = (\alpha + j\beta).$$

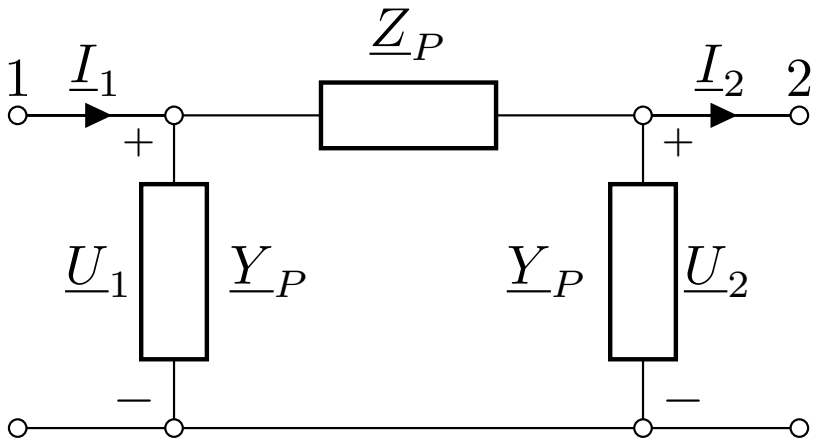
$$\underline{Z}_C = \sqrt{\frac{\underline{z}}{\underline{y}}} = \sqrt{\frac{r + jx}{g}}.$$

$$\underline{U}(x) = \underline{U}_2 \cdot \mathrm{ch}\underline{\gamma}(l - x) + \underline{Z}_C \cdot \underline{I}_2 \cdot \mathrm{sh}\underline{\gamma}(l - x),$$
$$\underline{I}(x) = \frac{\underline{U}_2}{\underline{Z}_C} \cdot \mathrm{sh}\underline{\gamma}(l - x) + \underline{I}_2 \cdot \mathrm{ch}\underline{\gamma}(l - x).$$

Кабли со неизолиран метален плашт, π-шема

$$\underline{Z}_P = \underline{Z}_C \cdot \mathrm{sh}\underline{\gamma} l,$$

$$\underline{Y}_P = \frac{\mathrm{ch}\underline{\gamma} l - 1}{\underline{Z}_C \cdot \mathrm{sh}\underline{\gamma} l}.$$



Влезна импеданција и изнесен потенцијал

$$\underline{k}_i = \frac{\underline{U}_2}{\underline{U}_1} = \frac{1}{\mathrm{ch}(\underline{\gamma} l) + \frac{\underline{Z}_C}{\underline{Z}_2} \cdot \mathrm{sh}(\underline{\gamma} l)}.$$

$$\underline{Z}_{\mathrm{vl}} = \underline{Z}_C \cdot \frac{\mathrm{ch}(\underline{\gamma} l) + \frac{\underline{Z}_C}{\underline{Z}_2} \cdot \mathrm{sh}(\underline{\gamma} l)}{\mathrm{sh}(\underline{\gamma} l) + \frac{\underline{Z}_C}{\underline{Z}_2} \cdot \mathrm{ch}(\underline{\gamma} l)}.$$

„Долги“ кабли

$$l > l_d = 70 \cdot \sqrt{\rho}, \quad (\mathrm{m})$$

$$k_i \approx \frac{2 \cdot e^{-\alpha l}}{|1 + \underline{Z}_C / \underline{Z}_2|},$$

$$\underline{Z}_{vl} \approx \underline{Z}_C.$$

Влезна импеданција и изнесен потенцијал

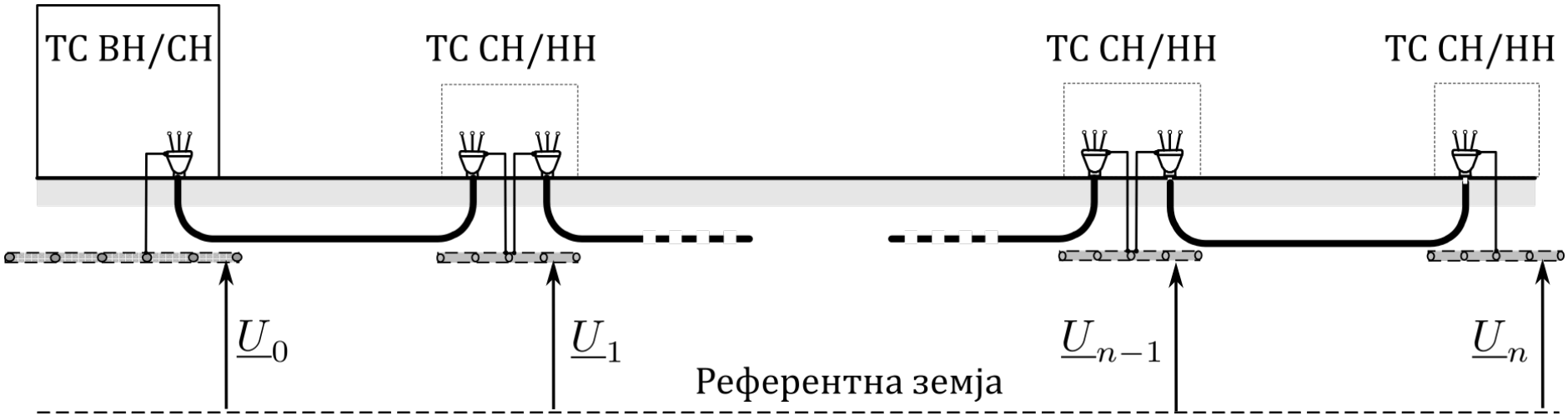
„Куси“ кабли

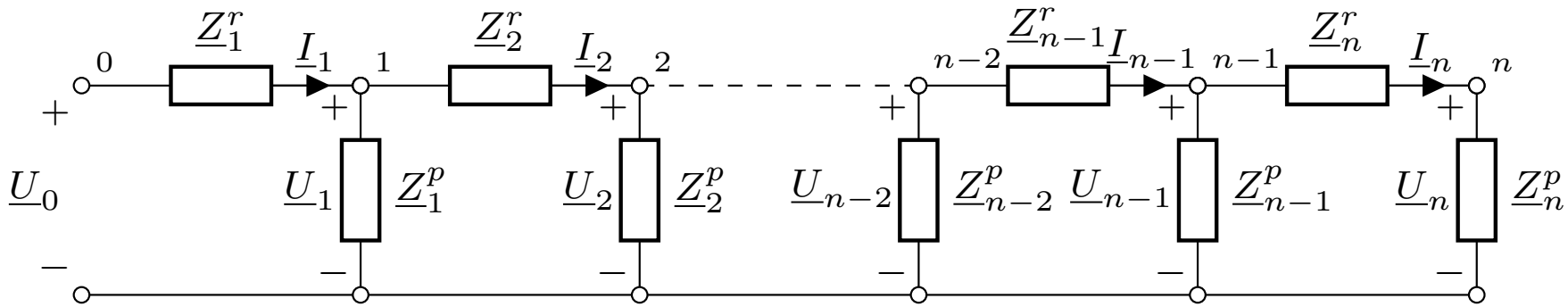
$$\left|\underline{\gamma}\right| \cdot l_k^2 = 2 \cdot \varepsilon.$$

$$k_i \approx \frac{1}{\left|1 + \dfrac{\underline{z} \cdot l}{\underline{Z}_2}\right|},$$

$$\underline{Z}_{vl} \approx \frac{\underline{Z}_2 + \underline{z} \cdot l}{1 + \underline{Z}_2 \cdot g \cdot l} = \frac{\underline{Z}_2 + \underline{z} \cdot l}{1 + \underline{Z}_2 / R_Z}.$$

Кабли со изолиран метален плашт



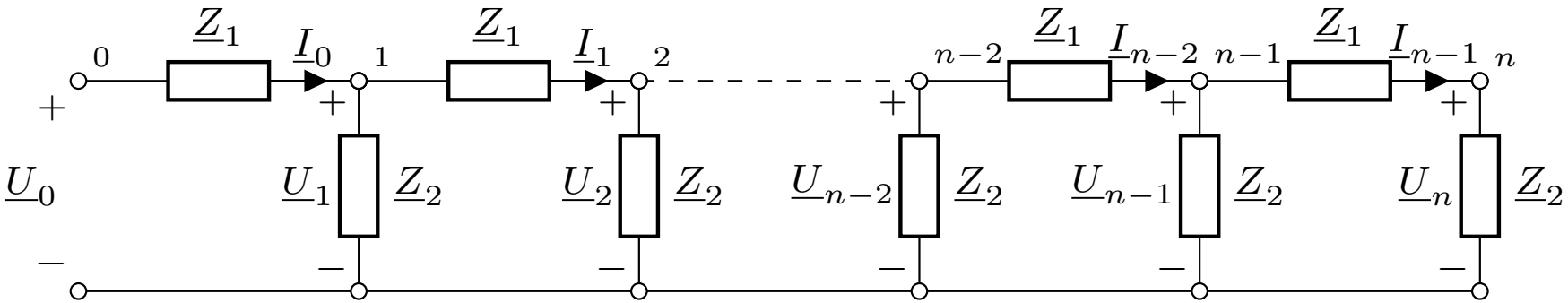


$$\underline{Z}_j^r = \underline{z} \cdot l_j = (r + jx) \cdot l_j,$$

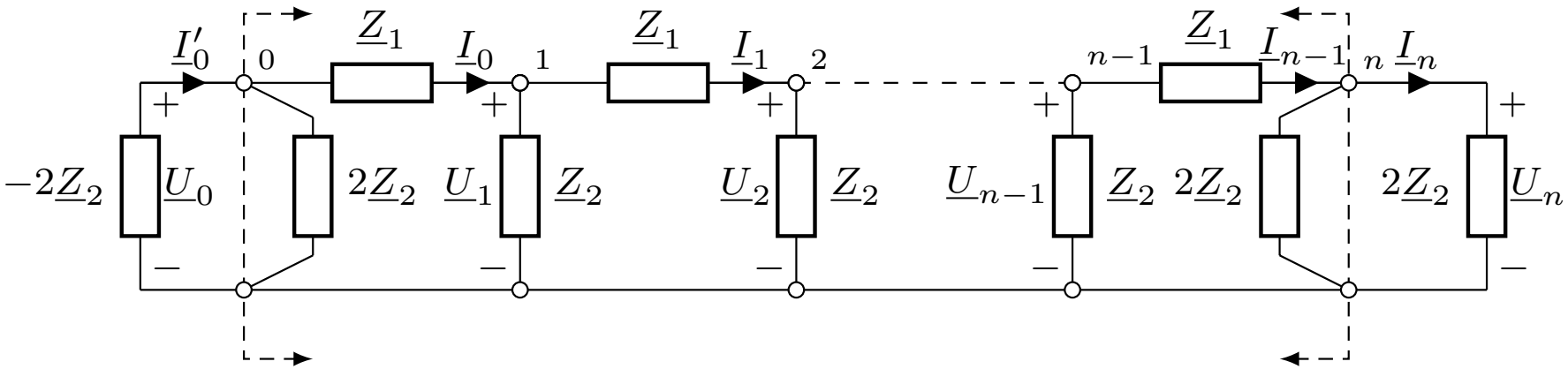
Кабли со изолиран метален плашт – идеализиран случај

$$\underline{Z}_1^r = \underline{Z}_2^r = \cdots = \underline{Z}_n^r = \underline{Z}_1.$$

$$\underline{Z}_1^p = \underline{Z}_2^p = \cdots = \underline{Z}_n^p = \underline{Z}_2,$$



Кабли со изолиран метален плашт – идеализиран случај



$$\underline{U}_0 = \underline{U}_n \cdot \mathrm{ch}(n\underline{g}) + \underline{Z} \cdot \underline{I}_n \cdot \mathrm{sh}(n\underline{g}),$$

$$\underline{I}'_0 = \frac{\underline{U}_n}{\underline{Z}} \cdot \mathrm{sh}(n\underline{g}) + \underline{I}_n \cdot \mathrm{ch}(n\underline{g}).$$

$$\underline{g} = \ln\left(1 + \frac{\underline{Z}_1}{2\underline{Z}_2} + \sqrt{2 \cdot \frac{\underline{Z}_1}{2\underline{Z}_2} + \frac{\underline{Z}_1^2}{4\underline{Z}_2^2}}\right),$$

$$\underline{Z} = \sqrt{\frac{\underline{Z}_1 \cdot 2\underline{Z}_2}{2 + \frac{\underline{Z}_1}{2\underline{Z}_2}}} = \frac{\underline{Z}_1}{\sqrt{2 \cdot \frac{\underline{Z}_1}{2\underline{Z}_2} + \frac{\underline{Z}_1^2}{4\underline{Z}_2^2}}}.$$

Кабли со изолиран метален плашт – идеализиран случај

$$\underline{I}_n = \frac{\underline{U}_n}{2\underline{Z}_2},$$

$$\underline{U}_0 = \underline{U}_n \left[\mathrm{ch}(n\underline{g}) + \frac{\underline{Z}}{2\underline{Z}_2} \cdot \mathrm{sh}(n\underline{g}) \right],$$

$$\underline{U}_n = \frac{\underline{U}_0}{\mathrm{ch}(n\underline{g}) + \dfrac{\underline{Z}}{2\underline{Z}_2} \cdot \mathrm{sh}(n\underline{g})}.$$

$$\underline{U}_k = \underline{U}_n \left[\mathrm{ch}\,(n-k)\,\underline{g} + \frac{\underline{Z}}{2\underline{Z}_2} \mathrm{sh}(n-k)\underline{g} \right], \quad k = 1, 2, \ldots, n.$$

$$u(k) = \frac{|\underline{U}_k|}{|\underline{U}_0|} = \frac{\left| \mathrm{ch}\,(n-k)\,\underline{g} + \dfrac{\underline{Z}}{2\underline{Z}_2} \mathrm{sh}(n-k)\underline{g} \right|}{\left| \mathrm{ch}(n\underline{g}) + \dfrac{\underline{Z}}{2\underline{Z}_2} \cdot \mathrm{sh}(n\underline{g}) \right|}.$$

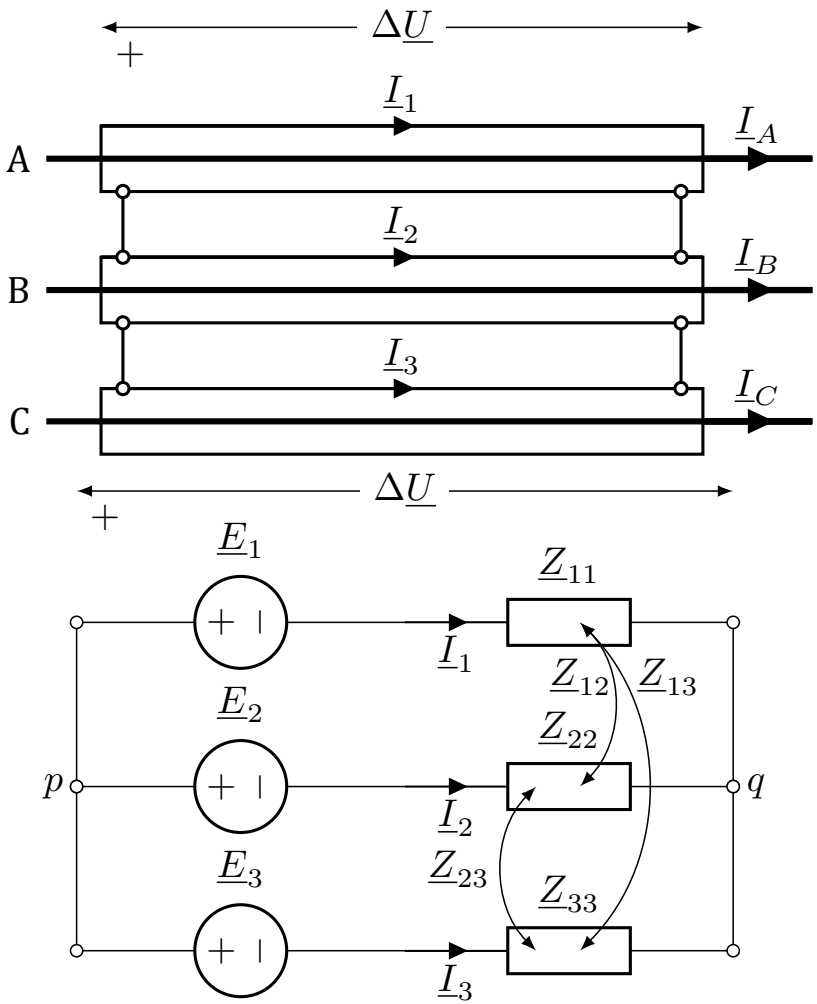
Кабли со изолиран метален плашт – идеализиран случај

$$\underline{I}_0 = \frac{\underline{U}_0 - \underline{U}_1}{\underline{Z}_1},$$

$$\underline{Z}_{vl} = \frac{\underline{U}_0}{\underline{I}_0}.$$

$$\underline{Y}_{vl} = \frac{1}{\underline{Z}_1} \cdot \frac{\mathrm{sh}(n\underline{g}) + \dfrac{\underline{Z}}{2\underline{Z}_2} \cdot \mathrm{ch}(n\underline{g})}{\mathrm{ch}(n\underline{g}) + \dfrac{\underline{Z}}{2\underline{Z}_2} \cdot \mathrm{sh}(n\underline{g})} - \frac{1}{2\underline{Z}_2}; \qquad \underline{Z}_{vl} = \frac{1}{\underline{Y}_{vl}}.$$

Егзактен модел со уважување на индуктивните спреги



$$\Delta \underline{\boldsymbol{U}} = \underline{\boldsymbol{U}}_p - \underline{\boldsymbol{U}}_q = \underline{\boldsymbol{E}} + \underline{\boldsymbol{Z}} \cdot \underline{\boldsymbol{I}}.$$

Егзактен модел со уважување на индуктивните спреги

$$\underline{Z}_{ij} = 0,05 \cdot l + j \cdot 0,1445 \cdot \log \frac{D_{ek}}{d_{ij}} \cdot l; \quad i,j = 1,2,3; \quad j \neq i,$$

$$\underline{Z}_{ii} = 0,05 \cdot l + r_e \cdot l + j \cdot 0,1445 \cdot \log \frac{D_{ek}}{d_e/2} \cdot l; \quad i = 1,2,3.$$

$$\underline{E}_i = \underline{M}_{iA} \cdot \underline{I}_A + \underline{M}_{iB} \cdot \underline{I}_B + \underline{M}_{iC} \cdot \underline{I}_C; \quad i = 1,2,3.$$

$$\underline{\boldsymbol{I}} = \underline{\boldsymbol{Z}}^{-1} \cdot (\Delta \underline{\boldsymbol{U}} - \underline{\boldsymbol{E}}).$$

$$\underline{Z}_e = \frac{\Delta \underline{U}}{\sum_{i=1}^{3} \underline{I}_i}.$$

$$\Delta \underline{\boldsymbol{U}} = \Delta \underline{U} \cdot \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}^{\mathrm{T}}, \quad \underline{\boldsymbol{E}} = 0$$

$$\underline{\boldsymbol{I}} = \Delta \underline{U} \cdot \underline{\boldsymbol{Z}}^{-1} \cdot \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}^{\mathrm{T}}.$$

Егзактен модел со уважување на индуктивните спреги

$$\underline{\boldsymbol{Y}} = \underline{\boldsymbol{Z}}^{-1}$$

$$\underline{\boldsymbol{I}} = \Delta \underline{U} \cdot \left[\begin{array}{ccc} \sum_{j=1}^{3} \underline{Y}_{1j} & \sum_{j=1}^{3} \underline{Y}_{2j} & \sum_{j=1}^{3} \underline{Y}_{3j} \end{array} \right]^{\mathrm{T}},$$

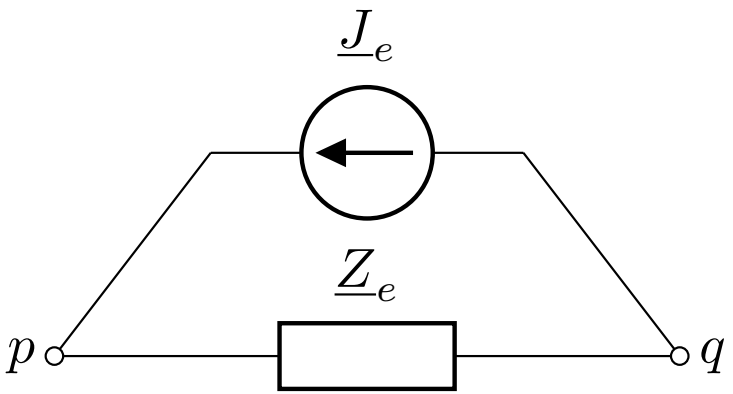
$$\underline{Z}_e = \frac{1}{\sum_{i=1}^{3} \sum_{j=1}^{3} \underline{Y}_{ij}}.$$

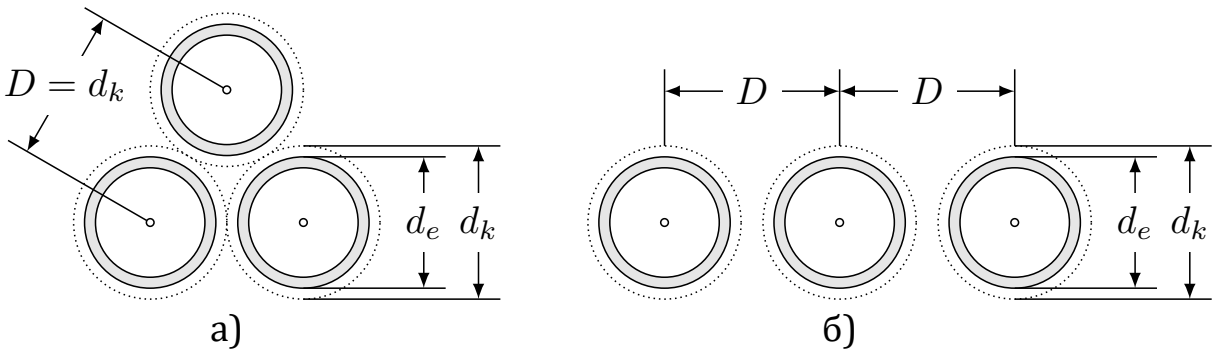
$$\underline{\boldsymbol{J}} = \underline{\boldsymbol{Y}} \cdot \underline{\boldsymbol{E}},$$

$$\underline{J}_i = \sum_{j=1}^{3} \underline{Y}_{ij} \cdot \underline{E}_j, \quad i = 1, 2, 3.$$

$$\underline{J}_e = \sum_{i=1}^{3} \underline{J}_i = \sum_{i=1}^{3} \sum_{j=1}^{3} \underline{Y}_{ij} \cdot \underline{E}_j.$$

Егзактен модел со уважување на индуктивните спреги





Триаголен распоред

$$\underline{\boldsymbol{Z}} = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_s & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_m & \underline{Z}_s \end{bmatrix},$$

Егзактен модел со уважување на индуктивните спреги

Триаголен распоред

$$\underline{Z}_s = \left(0,05 + r_e + j \cdot 0,1445 \cdot \log \frac{D_{ek}}{d_e/2}\right) \cdot l,$$

$$\underline{Z}_m = \left(0,05 + j \cdot 0,1445 \cdot \log \frac{D_{ek}}{D}\right) \cdot l.$$

$$\underline{Z}_e = \frac{\underline{Z}_s + 2 \cdot \underline{Z}_m}{3},$$

$$\underline{J}_e = \frac{\underline{M}_s + 2 \cdot \underline{M}_m}{\underline{Z}_s + 2 \cdot \underline{Z}_m} \cdot \underline{I}_{KV},$$

$$\underline{E}_e = \underline{Z}_e \cdot \underline{J}_e = \frac{\underline{M}_s + 2 \cdot \underline{M}_m}{3} \cdot \underline{I}_{KV}.$$

$$\underline{r}_f = \frac{\underline{I}_{KV} - \underline{J}_e}{\underline{I}_{KV}} = 1 - \frac{\underline{J}_e}{\underline{I}_{KV}} = 1 - \frac{\underline{M}_s + 2 \cdot \underline{M}_m}{\underline{Z}_s + 2 \cdot \underline{Z}_m}.$$

Егзактен модел со уважување на индуктивните спреги

Хоризонтален распоред

$$\underline{\boldsymbol{Z}} = \begin{bmatrix} \underline{Z}_s & \underline{Z}_{m1} & \underline{Z}_{m2} \\ \underline{Z}_{m1} & \underline{Z}_s & \underline{Z}_{m1} \\ \underline{Z}_{m2} & \underline{Z}_{m1} & \underline{Z}_s \end{bmatrix},$$

$$\underline{Z}_s = \left(0,05 + r_e + 0,1445 \cdot \log \frac{D_{ek}}{d_e/2}\right) \cdot l,$$

$$\underline{Z}_{m1} = \left(0,05 + 0,1445 \cdot \log \frac{D_{ek}}{D}\right) \cdot l,$$

$$\underline{Z}_{m2} = \left(0,05 + 0,1445 \cdot \log \frac{D_{ek}}{2D}\right) \cdot l.$$

Егзактен модел со уважување на индуктивните спреги

Хоризонтален распоред

$$\underline{Z}_e = \underline{Z}_s - \frac{2 \cdot (\underline{Z}_s - \underline{Z}_{m1})^2}{3\underline{Z}_s - 4\underline{Z}_{m1} + \underline{Z}_{m2}},$$

$$\underline{J}_e = \underline{I}_{KV} \cdot \frac{\underline{Z}_{m2} \cdot \underline{M}_1 + \underline{Z}_s \cdot (\underline{M}_s + \underline{M}_{m1} + \underline{M}_{m2})}{\underline{Z}_s^2 - 2\underline{Z}_{m1}^2 + \underline{Z}_s \cdot \underline{Z}_{m2}} -$$

$$- \underline{I}_{KV} \cdot \underline{Z}_{m1} \cdot \frac{(\underline{M}_s + 2\underline{M}_{m1} + \underline{M}_{m2})}{\underline{Z}_s^2 - 2\underline{Z}_{m1}^2 + \underline{Z}_s \cdot \underline{Z}_{m2}},$$

$$\underline{r}_f = 1 - \frac{\underline{J}_e}{\underline{I}_{KV}} = 1 - \frac{\underline{Z}_{m2} \cdot \underline{M}_1 + \underline{Z}_s \cdot (\underline{M}_s + \underline{M}_{m1} + \underline{M}_{m2})}{\underline{Z}_s^2 - 2\underline{Z}_{m1}^2 + \underline{Z}_s \cdot \underline{Z}_{m2}} +$$

$$+ \underline{Z}_{m1} \cdot \frac{(\underline{M}_s + 2\underline{M}_{m1} + \underline{M}_{m2})}{\underline{Z}_s^2 - 2\underline{Z}_{m1}^2 + \underline{Z}_s \cdot \underline{Z}_{m2}}.$$

Пример 1

Еден 10 kV кабел од типот IPO 13 3×95 6/10 kV и со должина $l = 0,75$ km е положен во земја со $\rho = 100\,\Omega$m на длабочина $h = 0,7$ m. Надворешниот пречник на кабелот изнесува $d_k = 4,5$ cm. На крајот од кабелот е приклучена ТС СН/НН со импеданција на заштитното заземјување изнесува $\underline{Z}_2 = R_2 = 5\,\Omega$. Импеданција по единица должина на металниот плашт заедно со челичната арматура е $\underline{z} = (0,7 + j2)\,\Omega$/km. Потребно е да се пресмета

а) влезната импеданција на кабелот $\underline{Z}_{vl}$;

б) граничната должина l_d после која кабелот може да се смета за долг;

в) коефициентот на изнесување на потенцијалот $\underline{k}_i$;

г) параметрите $\underline{Z}_P$ и $\underline{Y}_P$ на π-заменската шема на кабелот.

Пример 1

$$R_Z = \frac{\rho}{\pi \cdot l} \cdot \ln \frac{l}{\sqrt{h \cdot d_k}} = \frac{100}{\pi \cdot 750} \cdot \ln \frac{750}{\sqrt{0,7 \cdot 0,045}} = 0,354\,\Omega;$$

$$Y_Z = \frac{1}{R_Z} = 2,822\,\mathrm{S};$$

$$\underline{y} = g = \frac{Y_Z}{l} = \frac{2,822}{0,75} = 3,763\,\frac{\mathrm{S}}{\mathrm{km}}.$$

$$\underline{\gamma} = \sqrt{\underline{z} \cdot \underline{y}} = \sqrt{(0,7 + j2) \cdot 3,763} = (2,303 + j1,634)\,\mathrm{km}^{-1};$$

$$\underline{Z}_C = \sqrt{\frac{\underline{z}}{\underline{y}}} = \sqrt{\frac{0,7 + j2}{3,763}} = (0,612 + j0,434)\,\Omega = 0,75 \cdot e^{j35,4^\circ}\,\Omega.$$

$$\underline{Z}_{\mathrm{vl}} = \underline{Z}_C \cdot \frac{\mathrm{ch}(\underline{\gamma} l) + \dfrac{\underline{Z}_C}{\underline{Z}_2} \cdot \mathrm{sh}(\underline{\gamma} l)}{\mathrm{sh}(\underline{\gamma} l) + \dfrac{\underline{Z}_C}{\underline{Z}_2} \cdot \mathrm{ch}(\underline{\gamma} l)} = (0,596 + j0,401)\,\Omega = 0,719 \cdot e^{j34^\circ}\,\Omega.$$

Пример 1

$$l_d = -\frac{\ln \varepsilon}{2\alpha} = -\frac{\ln 0,05}{2 \cdot 2,303} = 0,65\,\text{km}.$$

$$\underline{k}_i = \frac{1}{\text{ch}(\underline{\gamma} l) + \frac{\underline{Z}_C}{\underline{Z}_2} \cdot \text{sh}(\underline{\gamma} l)} = (0,089 - j0,31) = 0,323 \cdot e^{-j73,9^\circ}.$$

$$k_i \approx \frac{2 \cdot e^{-\alpha l}}{|1 + \underline{Z}_C / \underline{Z}_2|} = \frac{2 \cdot e^{-2,303 \cdot 0,75}}{1,12576} = \frac{0,3556}{1,12576} = 0,316,$$

$$\underline{Z}_{vl} \approx \underline{Z}_C = (0,612 + j0,434)\,\Omega = 0,75 \cdot e^{j35,4^\circ}\,\Omega.$$

$$\underline{Z}_P = \underline{Z}_C \cdot \text{sh}\underline{\gamma} l = (-0,6211 + j2,0713) = 2,162 \cdot e^{j106,7^\circ}\,\Omega,$$

$$\underline{Y}_P = \frac{\text{ch}\underline{\gamma} l - 1}{\underline{Z}_C \cdot \text{sh}\underline{\gamma} l} = 1,185 \cdot e^{-j16,3^\circ}\,\text{S}.$$

Пример 1

../programi/kabli/neizolian_param.m

```
1  function [Zvl,k,Zp,Yp] = neizolian_param(rho,l,h,dk,z,Z2)
2  Rz = rho/(pi*l*1000)*log(l*1000/sqrt(h*dk));
3  g = 1/(Rz*l);
4  gama = sqrt(z*g);
5  Zc = sqrt(z/g);
6  Zvl = Zc*(cosh(gama*l) + Zc/Z2*sinh(gama*l)) ...
7      /(sinh(gama*l) + Zc/Z2*cosh(gama*l));
8  k = 1/(cosh(gama*l) + Zc/Z2*sinh(gama*l));
9  Zp = Zc*sinh(gama*l);
10 Yp = (cosh(gama*l)-1)/Zp;
```

```
>> [Zvl,k,Zp,Yp] = neizolian_param(100,0.75,0.7,0.045,0.7+2j,5)
Zvl = 0.5962 + 0.4015i
k =   0.0894 - 0.3101i
Zp = -0.6211 + 2.0713i
Yp =  1.1376 - 0.3326i
```

Пример 2

Да се пресмета вредноста на влезната импеданција $\underline{Z}_{vl}$ на кабелот од претходниот пример за случајот кога неговата челична арматура е во заситена состојба така што неговата надолжна импеданција изнесува $z = (0,7 + j0,7)\,\Omega$/km. Колкав ќе биде коефициентот на изнесениот потенцијал $\underline{k}_i$ во овој случај?

```
>> [Zvl,k,Zp,Yp] = neizolian_param(100,0.75,0.7,0.045,0.7+0.7j,5)
Zvl =
   0.5133 + 0.1515i
k =
   0.4025 - 0.2402i
Zp =
   0.5044 + 0.8035i
Yp =
   1.2426 - 0.1301i
```

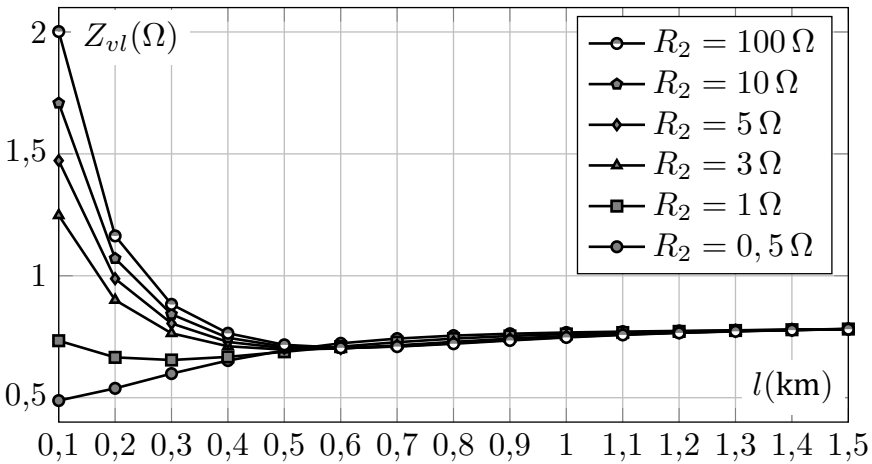
$$\underline{Z}_{vl} = 0,535 \cdot e^{j16,4^\circ}\,\Omega; \quad \underline{k}_i = 0,469 \cdot e^{-j30,8^\circ},$$

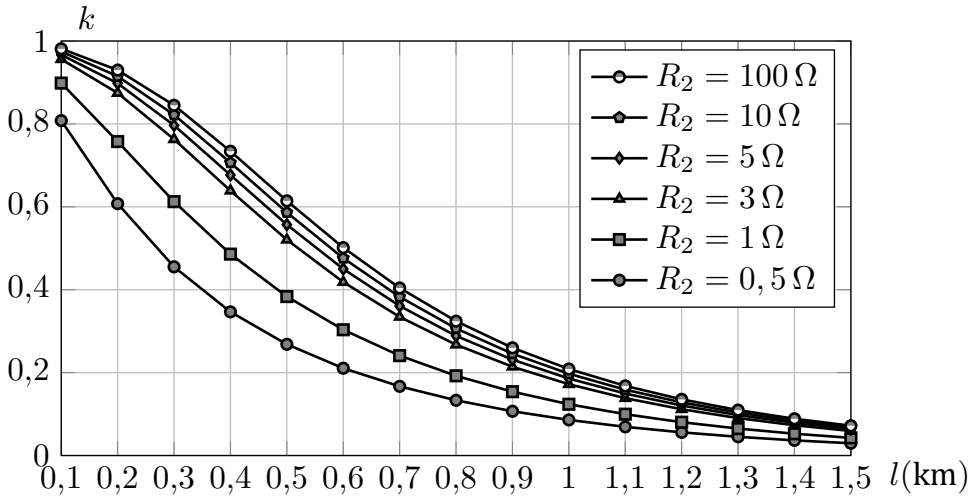
Пример 3

Да се пресмета зависноста на $\underline{Z}_{vl}$ од должината l на кабелот од примерот 1 при $\underline{z} = (0,7 + j2)\,\Omega$ и $R_2 \in \{0,5; 1; 3; 5; 10; 100\}\ \Omega$.

../programi/kabli/kabel_3.m

```
clear;
 l = (0.1:0.1:1.5)';
Z2 = [0.5 1 3 5 10 100]';
for i = 1:length(l)
  for j = 1:length(Z2)
      [Zvl(i,j),k(i,j)] = ...
          neizolian_param(100,l(i),0.7,0.045,0.7+2j,Z2(j));
  end
end
figure; plot(l,abs(Zvl)); grid;
figure; plot(l,abs(k)); grid;
```





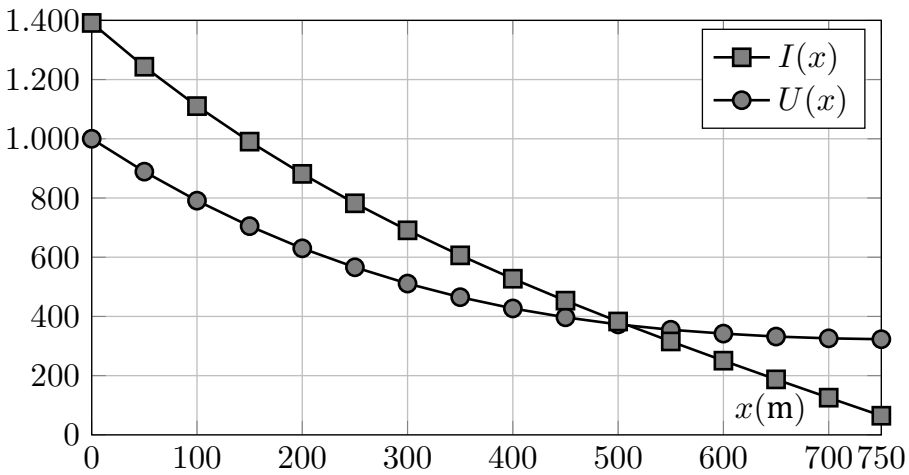
Пример 4

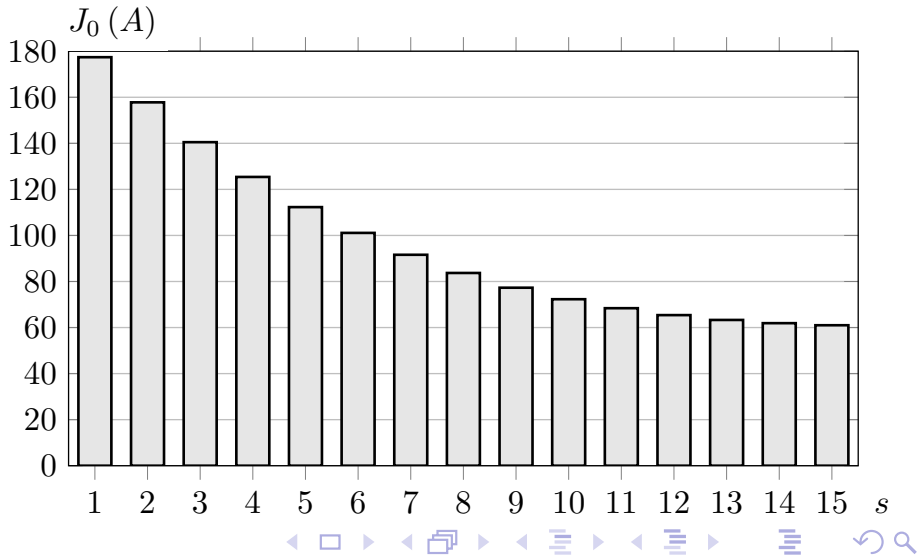
За кабелот од примерот 1 е познат напонот $U_1 = 1000$ V. Да се пресметаат $I(x)$ и $U(x)$, како и струјата на одведување во земјата од плаштот $J_0(x)$.

$$\underline{U}(x) = \underline{U}_1 \cdot \mathrm{ch}\underline{\gamma} x - \underline{Z}_C \cdot \underline{I}_1 \cdot \mathrm{sh}\underline{\gamma} x,$$

$$\underline{I}(x) = -\frac{\underline{U}_1}{\underline{Z}_C} \cdot \mathrm{sh}\underline{\gamma} x + \underline{I}_1 \cdot \mathrm{ch}\underline{\gamma} x.$$

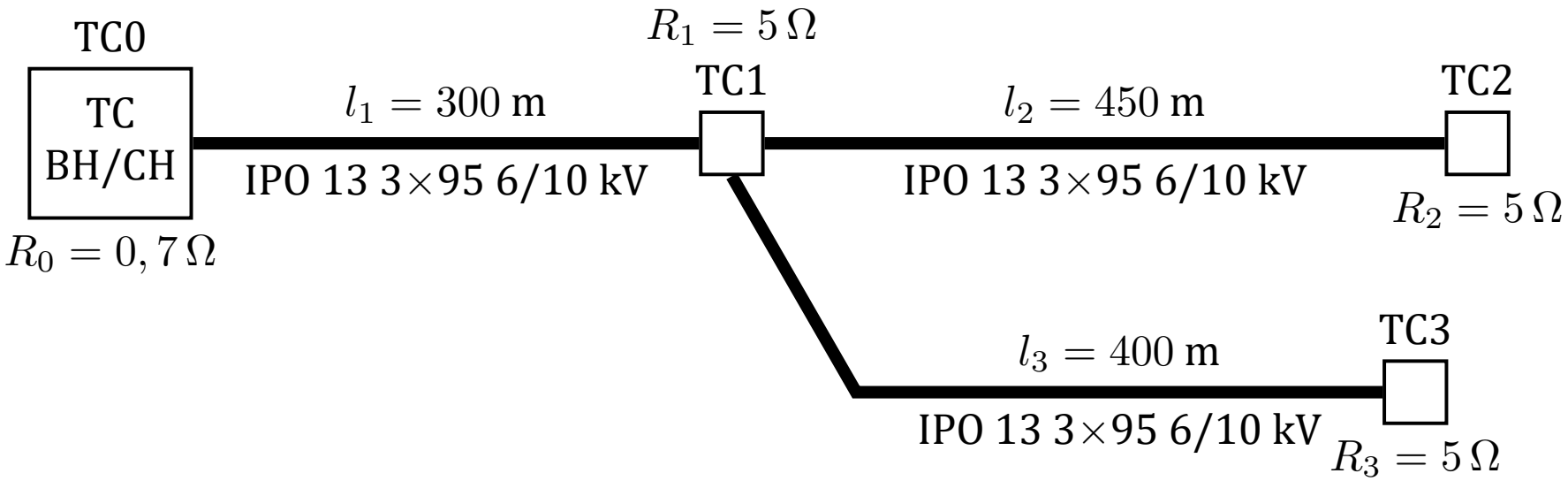
$$\underline{I}_1 = \frac{\underline{U}_1}{\underline{Z}_{vl}} = \frac{1000}{0,719 \cdot e^{j34^\circ}} = (1154 - j777,1) = 1391,3 \cdot e^{-j34^\circ}\,\mathrm{A}.$$





Пример 5

Во делница долга $l = 750$ m (пример 1) се вметнува ТС1 на растојание $l_1 = 300$ m од почетокот. Од ТС1 се полага кабел кон ТС3 со должина $l_3 = 400$ m. Да се пресмета влезната импеданција на почетокот на кабелскиот извод $\underline{Z}_{vl.1}$. Колкави се струите и напоните во заземјувачкиот систем од прикажаната кабелска мрежа за случајот кога во мрежестиот заземјувач од ТС ВН/СН, чија што отпорност на распростирање изнесува $R_0 = 0,7\,\Omega$, се инјектира струја на доземен спој $J_0 = 1$ kA. Сите ТС СН/НН имаат исти вредности на отпорностите на распростирање на заштитното заземјување $R_1 = R_2 = R_3 = 5\,\Omega$.

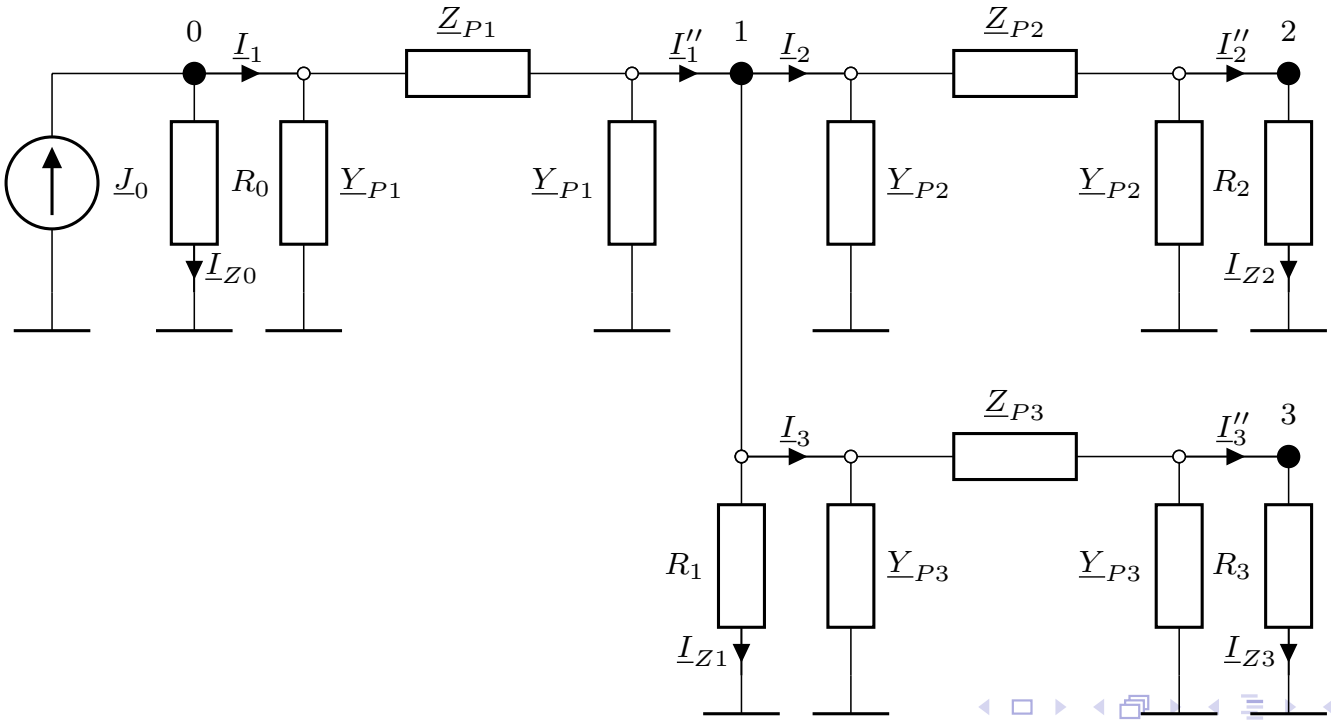


Пример 5

Секција	$\underline{Z}_P\,(\Omega)$	$\underline{Y}_P\,(\mathrm{S})$
TC0 – TC1	$0,14034 + j0,65136$	$0,61750 – j0,03790$
TC1 – TC2	$0,08167 + j1,05700$	$0,84507 – j0,10671$
TC1 – TC3	$0,11637 + j0,91395$	$0,77440 – j0,07954$

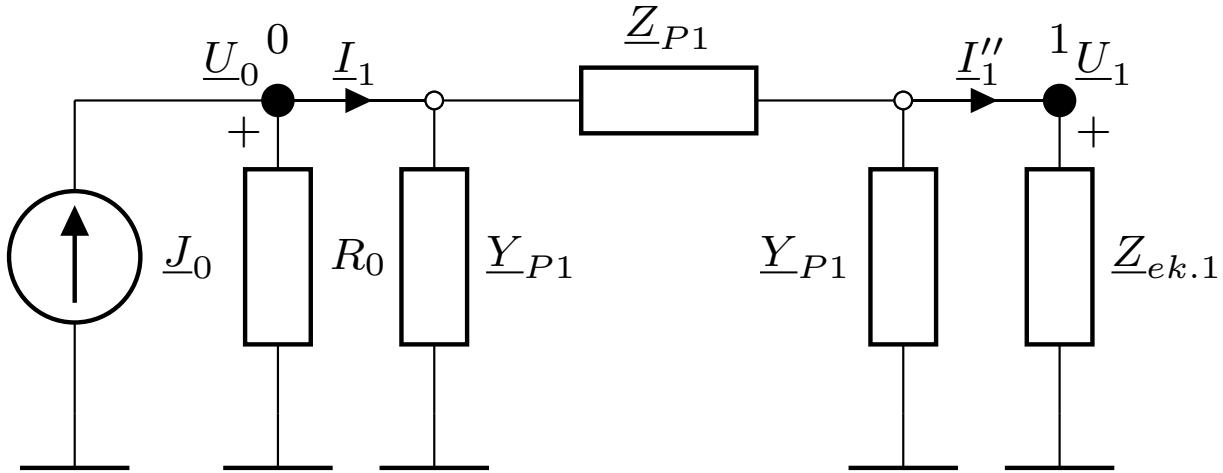
$$\underline{Z}_{vl.2} = (0,64594 + j0,29855) = 0,7116 \cdot e^{j24,8^\circ}\,\Omega; \qquad \underline{k}_{i.2} = 0,616 \cdot e^{-j42,4^\circ}$$

$$\underline{Z}_{vl.3} = (0,67522 + j0,27401) = 0,72870 \cdot e^{j22,1^\circ}\,\Omega; \qquad \underline{k}_{i.3} = 0,677 \cdot e^{-j36,6^\circ}$$



Пример 5

$$\underline{Z}_{ek.1} = \underline{Z}_{vl.2} \parallel \underline{Z}_{vl.3} \parallel R_1 = (0,31327 + j0,12607) = 0,33768 \cdot e^{j21,9^\circ}\,\Omega.$$



$$\underline{Z}_{vl.1} = \underline{Z}_C \cdot \frac{\operatorname{ch}(\underline{\gamma} l_1) + \dfrac{\underline{Z}_C}{\underline{Z}_2} \cdot \operatorname{sh}(\underline{\gamma} l_1)}{\operatorname{sh}(\underline{\gamma} l_1) + \dfrac{\underline{Z}_C}{\underline{Z}_2} \cdot \operatorname{ch}(\underline{\gamma} l_1)} = (0,46317 + j0,41965) =$$

$$= 0,62501 \cdot e^{j42,2^\circ}\,\Omega,$$

Пример 5

$$\underline{k}_{i.1} = \frac{1}{\mathrm{ch}(\underline{\gamma} l_1) + \dfrac{\underline{Z}_C}{\underline{Z}_{ek.1}} \cdot \mathrm{sh}(\underline{\gamma} l_1)} = (0,24523 - j0,22466) = 0,3326 \cdot e^{-j42,5^\circ}.$$

$$\underline{Z}_{ek} = R_0 \,\Pi\, \underline{Z}_{vl.1} = 0,7 \,\Pi\, 0,62501 \cdot e^{j42,2^\circ} = 0,35381 \cdot e^{j22,34^\circ}\,\Omega;$$

$$\underline{U}_0 = \underline{Z}_{ek} \cdot \underline{J}_0 = 353,81 \cdot e^{j22,34^\circ}\,\mathrm{V}.$$

$$\underline{I}_1 = \frac{\underline{U}_0}{\underline{Z}_{ek}} = \frac{353,81 \cdot e^{j22,34^\circ}}{0,62501 \cdot e^{j42,2^\circ}} = 566,084 \cdot e^{-j19,86^\circ}\,\mathrm{A};$$

$$\underline{U}_1 = \underline{k}_{i.1} \cdot \underline{U}_0 = 0,3326 \cdot e^{-j42,5^\circ} \cdot 353,81 \cdot e^{j22,34^\circ} = 117,7 \cdot e^{-j20,16^\circ}\,\mathrm{V};$$

$$\underline{I}_2 = \frac{\underline{U}_1}{\underline{Z}_{vl.2}} = \frac{117,7 \cdot e^{-j20,16^\circ}}{0,7116 \cdot e^{j24,8^\circ}} = 165,4 \cdot e^{-j44,96^\circ}\,\mathrm{A};$$

$$\underline{U}_2 = \underline{k}_{i.2} \cdot \underline{U}_1 = 0,616 \cdot e^{-j42,4^\circ} \cdot 117,7 \cdot e^{j22,34^\circ} = 72,5 \cdot e^{-j20,06^\circ}\,\mathrm{V};$$

$$\underline{I}_3 = \frac{\underline{U}_1}{\underline{Z}_{vl.3}} = \frac{117,7 \cdot e^{-j20,16^\circ}}{0,7287 \cdot e^{j22,1^\circ}} = 161,5 \cdot e^{-j42,26^\circ}\,\mathrm{A};$$

$$\underline{U}_3 = \underline{k}_{i.3} \cdot \underline{U}_1 = 0,677 \cdot e^{-j36,6^\circ} \cdot 117,7 \cdot e^{j22,34^\circ} = 79,7 \cdot e^{-j14,26^\circ}\mathrm{V}.$$

Пример 5

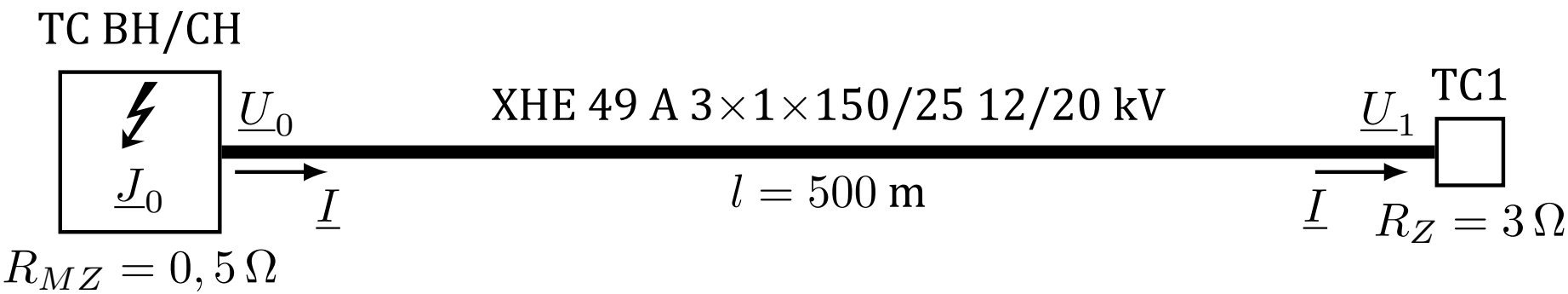
$$I_{Z0} = U_0/R_0 = 353,81/0,7 = 505,44\,\text{A};$$
$$I_{Z1} = U_1/R_1 = 117,7/5 = 23,54\,\text{A};$$
$$I_{Z2} = U_2/R_2 = 72,5/5 = 14,5\,\text{A};$$
$$I_{Z3} = U_3/R_3 = 79,7/5 = 15,94\,\text{A}.$$

Пример 6

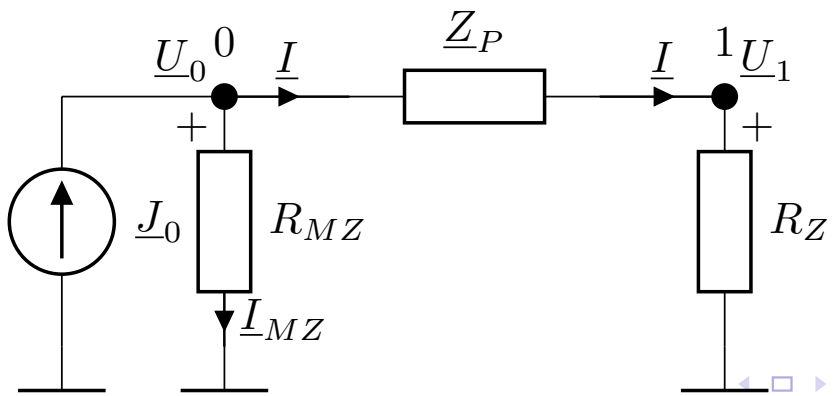
Трифазен кабелски вод со полиетиленска изолација, тип ХНЕ 49 А 3×1×150/25 12/20 kV, со должина $l = 500$ m напојува ТС СН/НН. За него се знае

$$\underline{z} = 0,29 + j0,668 = 0,728 \cdot e^{j66,5^\circ} \ \frac{\Omega}{\text{km}}. \tag{1}$$

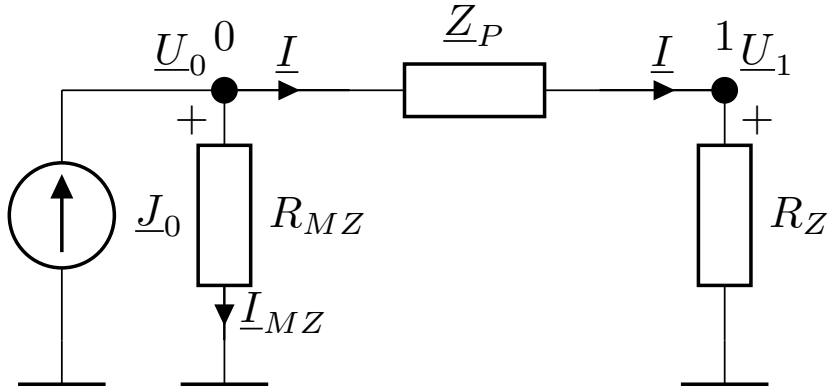
Да се пресмета струјата I на почетокот од кабелот ако $U_0 = 1000$ V.



$$\underline{Z}_P = \underline{z} \cdot l, \quad \underline{Y}_P = 0.$$



Пример 6



$$\underline{U}_1 = \frac{R_Z}{\underline{Z}_P + R_Z} \cdot \underline{U}_0 = \frac{3}{3,145 + j0,334} \cdot 1000 =$$

$$= (943,3 - j100,1) = 948,6 \cdot e^{-j6,1^\circ}\,\mathrm{V};$$

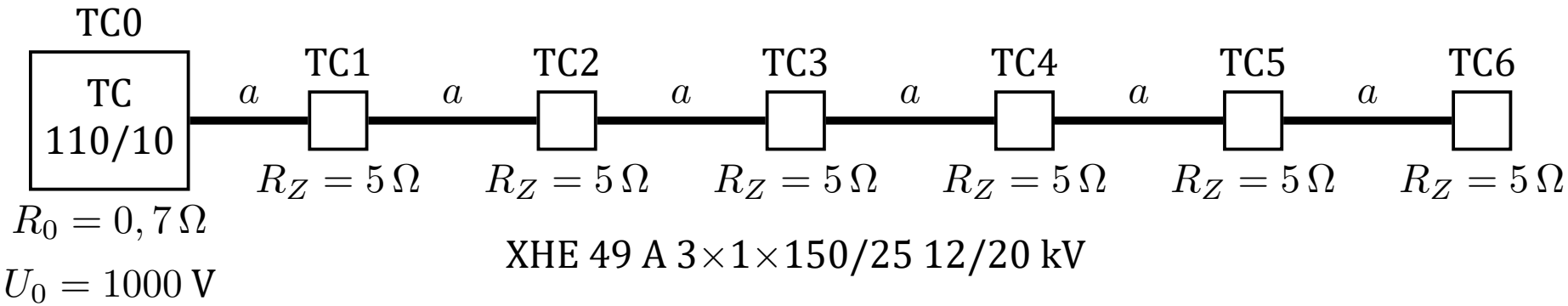
$$\underline{I} = \frac{\underline{U}_0}{\underline{Z}_P + R_Z} = \frac{1000}{3,145 + j0,334} = (314,4 - j33,4) = 316,2 \cdot e^{-j6,1^\circ}\,\mathrm{A}.$$

$$\underline{J}_0 = \underline{I}_{MZ} + \underline{I} = \frac{\underline{U}_0}{R_{MZ}} + \underline{I} = \frac{1000}{0,5} + (314,4 - j33,4) =$$

$$= (2314,4 - j33,4) = 2315 \cdot e^{-j0,83^\circ}\,\mathrm{A}.$$

Пример 7

Еден 10 kV кабелски извод, изведен со кабел тип XHE 49 A $3\times1\times150/25$ 12/20 kV, напојува $n = 6$ ТС СН/НН при што е познато $\underline{z} \cdot a = (0,145 + j0,334)\,\Omega$. Секоја ТС СН/НН има заземјувач со $\rho = 100\,\Omega$; $R_Z = 5\,\Omega$; $E_{\mathrm{d.max}} = 7,0\%$; $E_{\mathrm{c.max}} = 14\%$. Познат е $U_0 = 1000$ V. Да се пресметаат потенцијалите $\underline{U}_k\,(k = 1, 2, \ldots, n)$ што ги примаат заземјувачите на ТС СН/НН како и напоните на допир и чекор. Времето на исклучување на кусата врска извесува $t = 0,5$ s.



$$\underline{U}_0 = \underline{U}_n \cdot \mathrm{ch}(n\underline{g}) + \underline{Z}_C \cdot \underline{I}_n \cdot \mathrm{sh}(n\underline{g}),$$

$$\underline{I}_0 = \frac{\underline{U}_n}{\underline{Z}_C} \cdot \mathrm{sh}(n\underline{g}) + \underline{I}_n \cdot \mathrm{ch}(n\underline{g}).$$

Пример 7

$$\frac{\underline{Z}}{2R_Z} = \underline{\lambda} = \frac{0,145 + j0,334}{10} = (0,0145 + j0,0344) = 0,0364 \cdot e^{j66,5^\circ};$$

$$\underline{g} = \ln\left(1 + \underline{\lambda} + \sqrt{2 \cdot \underline{\lambda} + \underline{\lambda}^2}\right) = (0,2258 + j0,1472) = 0,2695 \cdot e^{j33,1^\circ};$$

$$\underline{Z}_C = \frac{\underline{Z}}{\sqrt{2 \cdot \underline{\lambda} + \underline{\lambda}^2}} = (1,1301 + j0,7281) = 1,3443 \cdot e^{j32,8^\circ}\,\Omega.$$

$$e^{n\underline{g}} = (2,4592 + j2,9950) = 3,8753 \cdot e^{j50,6^\circ};$$

$$e^{-n\underline{g}} = (0,1638 - j0,1994) = 0,2580 \cdot e^{-j50,6^\circ};$$

$$\mathrm{ch}(n\underline{g}) = \frac{e^{n\underline{g}} + e^{-n\underline{g}}}{2} = (1,3115 + j1,3978) = 1,9167 \cdot e^{j46,8^\circ};$$

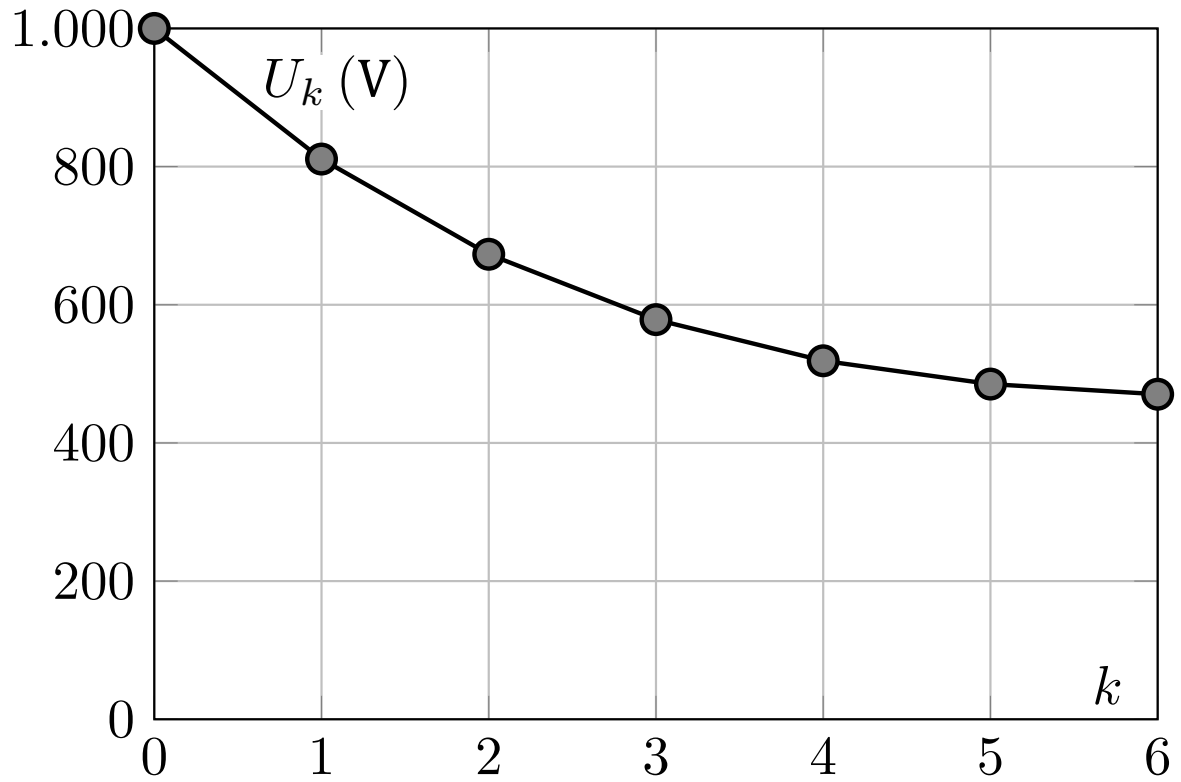
$$\mathrm{sh}(n\underline{g}) = \frac{e^{n\underline{g}} - e^{-n\underline{g}}}{2} = (1,1477 + j1,5972) = 1,9668 \cdot e^{j54,3^\circ}.$$

$$\underline{U}_n = \frac{\underline{U}_0}{\mathrm{ch}ng + \dfrac{\underline{Z}}{2R_Z} \cdot \mathrm{sh}ng} = (293,4 - j367,9) = 470,5 \cdot e^{-j0,51^\circ}\ \mathrm{V},$$

$$\underline{U}_k = \underline{U}_n \cdot \left[\mathrm{ch}\,(n-k)\,\underline{g} + \frac{\underline{Z}}{2R_Z} \cdot \mathrm{sh}(n-k) \cdot \underline{g}\right], \quad k = 1, 2, \ldots, n-1.$$

Пример 7

$\underline{U}_0$	$\underline{U}_1$	$\underline{U}_2$	$\underline{U}_3$
$1000 \cdot e^{j0^\circ}$	$810,9 \cdot e^{-j13,5^\circ}$	$673,1 \cdot e^{-j21,0^\circ}$	$578,5 \cdot e^{-j31,5^\circ}$
	$\underline{U}_4$	$\underline{U}_5$	$\underline{U}_6$
	$518,9 \cdot e^{-j40,8^\circ}$	$485,2 \cdot e^{-j47,7^\circ}$	$470,5 \cdot e^{-j51,4^\circ}$



Пример 7

$$\underline{I}_0 = \frac{\underline{U}_0 - \underline{U}_1}{\underline{Z}_1} = (586,5 - j350,7) = 683,3 \cdot e^{-j30,9^\circ}\ \text{A}.$$

$$\underline{Z}_{vl} = \frac{\underline{U}_0}{\underline{I}_0} = (1,256 + j0,751) = 1,463 \cdot e^{j30,9^\circ}\ \Omega.$$

$$E_{\text{c.max}} = 0,14 \cdot U_1 = 0,14 \cdot 810,9 = 113,5$$

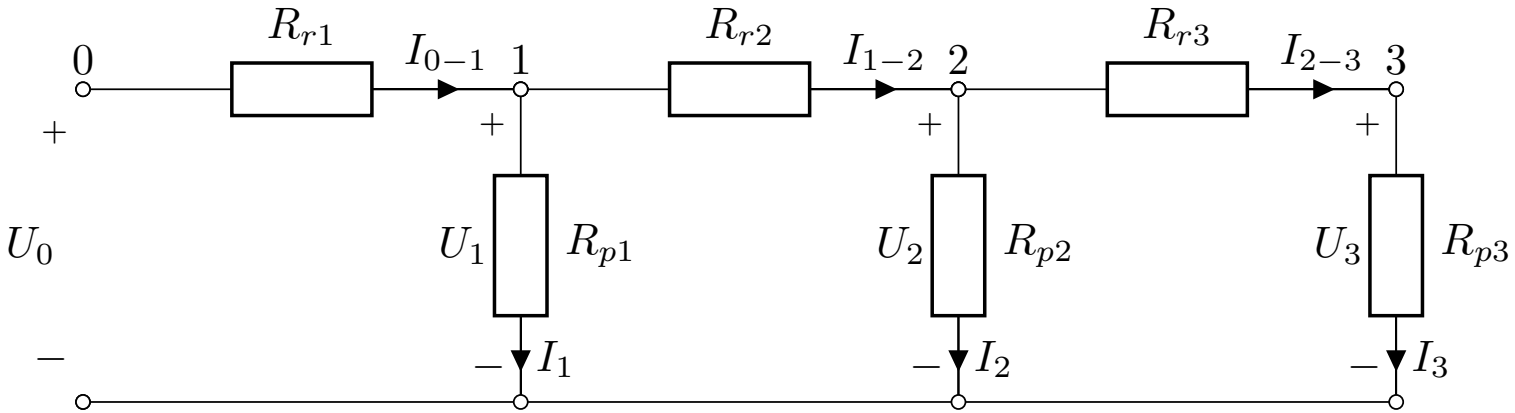
$$s_c = 1 + 6 \cdot \frac{\rho}{1000} = 1 + 6 \cdot \frac{125}{1000} = 1,75;$$

$$U_{\text{c. max}} = \frac{E_{\text{c. max}}}{s_c} = \frac{113,5}{1,75} = 64,9 < 80\,\text{V}.$$

Пример 8

Да се реши претходниот пример со постапката за решавање на електрични кола во форма на скала.

Прво ќе го решиме следното коло за кое се познати $U_0 = 100\,\text{V}$, $R_{r1} = R_{r2} = R_{r3} = 2\,\Omega$ и $R_{p1} = R_{p2} = R_{p3} = 1\,\Omega$.



$$I_3 = 1\,\text{A},$$

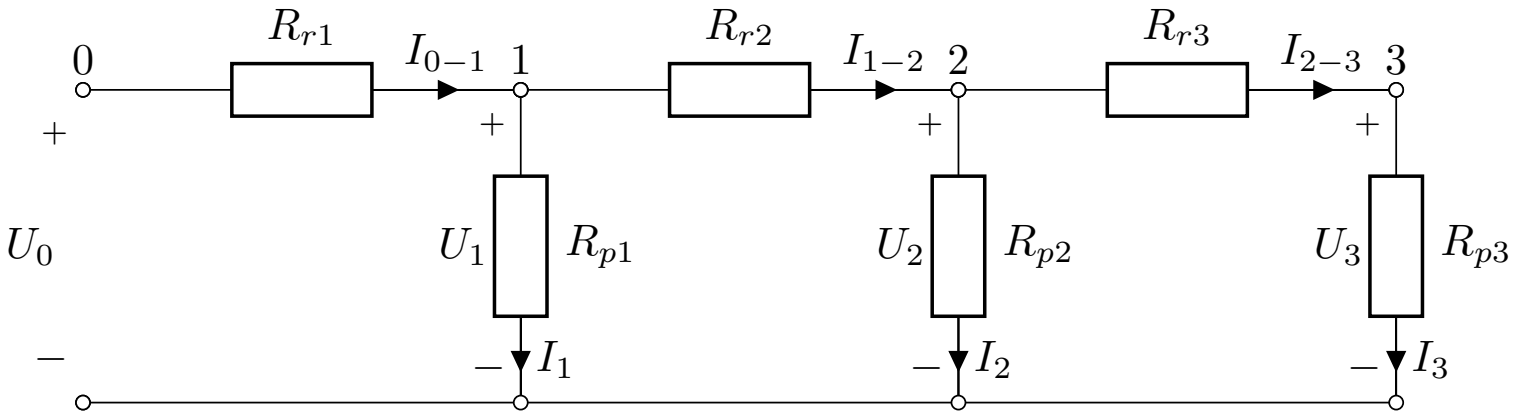
$$U_3 = R_{p3} \cdot I_3 = 1\,\text{V}.$$

$$I_{2-3} = I_3 = 1\,\text{A};$$

$$U_2 = U_3 + R_{r3} \cdot I_{2-3} = 1 + 2 \cdot 1 = 3\,\text{V};$$

$$I_2 = U_2 / R_{p2} = 3/1 = 3\,\text{A}.$$

Пример 8



$$I_{1-2} = I_2 + I_{2-3} = 3 + 1 = 4\,\text{A};$$
$$U_1 = U_2 + R_{r2} \cdot I_{1-2} = 3 + 2 \cdot 4 = 11\,\text{V};$$
$$I_1 = U_1 / R_{p1} = 11/1 = 11\,\text{A}.$$

$$I_{0-1} = I_1 + I_{1-2} = 11 + 4 = 15\,\text{A};$$
$$U_0 = U_1 + R_{r1} \cdot I_{0-1} = 11 + 2 \cdot 15 = 41\,\text{V}.$$

Претспоставка $I_3 = 1$ A не е точна бидејќи не добивме $U_0 = 100$ V, при што сме направиле грешка во пресметките за 100/41 = 2,439 пати.

Пример 8

$$U_0 = 100/41 \cdot 41 = 100\,\mathrm{V};$$
$$U_1 = 100/41 \cdot 11 = 26,8293\,\mathrm{V};$$
$$U_2 = 100/41 \cdot 3 = 7,3171\,\mathrm{V};$$
$$U_3 = 100/41 \cdot 1 = 2,4390\,\mathrm{V}.$$

$$I_1 = 26,8293\,\mathrm{A}; \qquad I_{0-1} = 36,5854\,\mathrm{A};$$
$$I_2 = 7,3171\,\mathrm{A}; \qquad I_{1-2} = 9,7561\,\mathrm{A};$$
$$I_3 = 2,4390\,\mathrm{A}; \qquad I_{2-3} = 2,4390\,\mathrm{A}.$$

$$R_{vl} = \frac{U_0}{I_{0-1}} = \frac{100}{36,5854} = 2,7333\,\Omega.$$

Пример 8

../programi/kabli/kabel_11.m

```
1  function kabel = kabel_11()
2  kabel.U0 = 1000;
3  kabel.Rz = 5*ones(6,1);
4  kabel.Zr = (0.145 + 1j*0.334)*ones(6,1);
```

../programi/kabli/skala.m

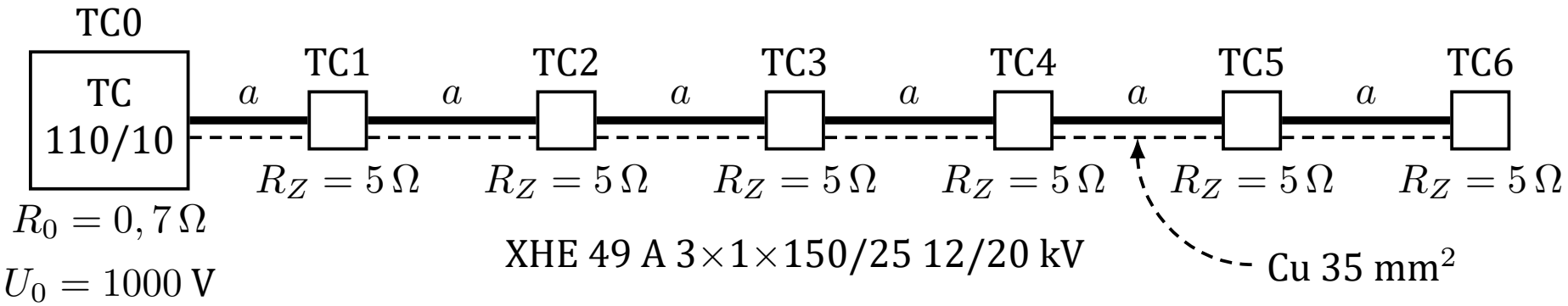
```
1  function [U, Ir, Iz] = skala(datoteka)
2  K = feval(datoteka);
3  [U0,Rz,Zr] = deal(K.U0,K.Rz,K.Zr);
4  n =length(Rz);
5  Iz(n,1) = 1;
6  Ir(n,1) = 1;
7  U(n,1) = Rz(n)*Iz(n);
8  for i = n-1:-1:1
9      U(i) = U(i+1) + Zr(i)*Ir(i+1);
10     Iz(i) = U(i)/Rz(i);
11     Ir(i) = Ir(i+1) + Iz(i);
12 end
13 U0_presm = U(1) + Zr(1)*Ir(1);
14 k = U0/U0_presm;
15 U = k*U;
16 Ir = k*Ir;
17 Iz = k* Iz;
```

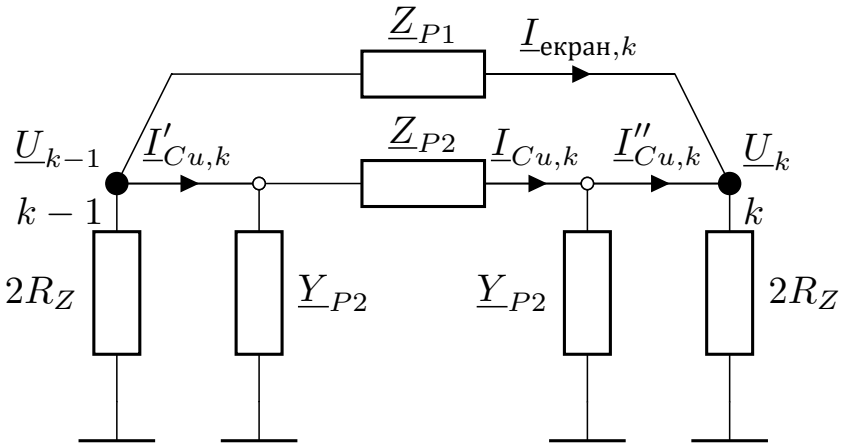
Пример 8

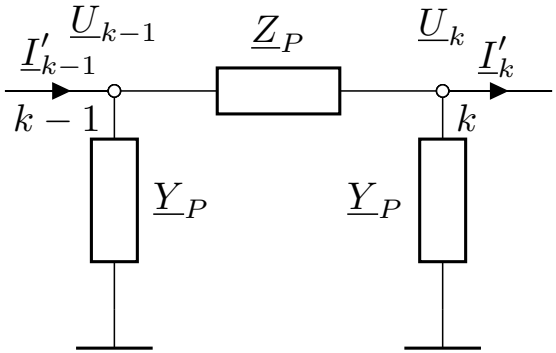
```
>> [U, Ir, Iz] = skala('kabel_11');
>> U = abs(U)
U =
  810.9036
  673.0965
  578.4978
  518.7252
  485.1763
  470.5123

>> Zvl = 1000/Ir(1)
Zvl =
   1.2560 + 0.7510i
```

Пример 9

Пресметките на извоз на потенцијалот за претходниот пример да се повторат и за случајот кога во кабелскиот ров, по целата негова должина, заедно со трите жили од кабелот тип XHE 49 A 3×1×150/25 12/20 kV, постои и бакарно јаже, положено на длабочина $h = 0,7$ m.

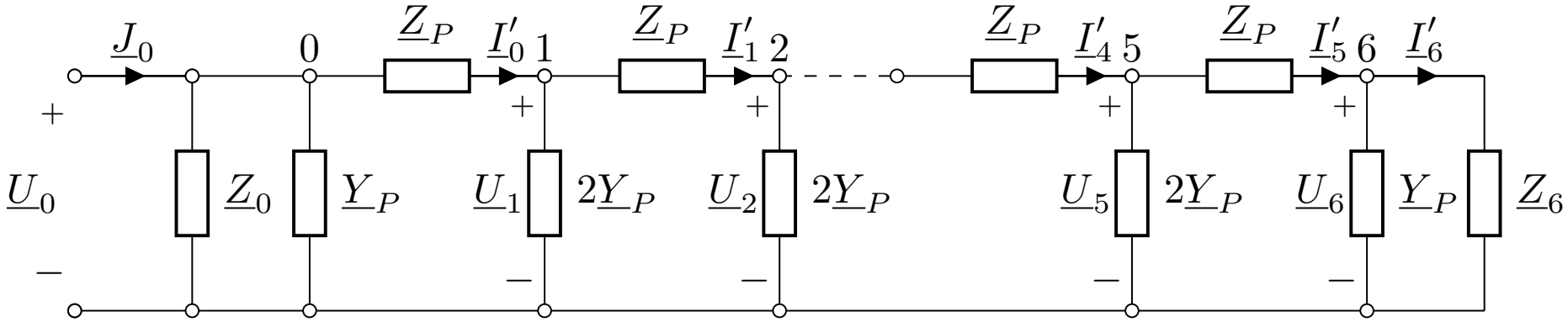






$$\underline{Y}_P = (0,9500 - j0,0472)\,\text{S}, \quad \underline{Z}_P = (0,0936 + j0,1948)\,\Omega$$

Пример 9



$$\underline{\boldsymbol{Y}} \cdot \underline{\boldsymbol{U}} = \underline{\boldsymbol{I}},$$

$$\underline{Y}_{ii} = 2\underline{Y}_P + \frac{2}{\underline{Z}_P}, \quad i = 1, 2, \ldots, 5,$$

$$\underline{Y}_{66} = \underline{Y}_P + \frac{1}{\underline{Z}_P} + \frac{1}{2R_Z},$$

$$\underline{Y}_{ij} = -\frac{1}{\underline{Z}_p}, \quad i, j = 1, 2, \ldots, 6; \quad i \neq j,$$

$$\underline{I}_1 = \frac{\underline{U}_0}{\underline{Z}_P}.$$

Пример 9

../programi/kabli/primer_12.m

```
1  U0 = 1000;
2  Zp = 0.0936 + 1j*0.1948;
3  Yp = 0.95   - 1j*0.0472;
4  Rz = 5;
5   n = 6;
6  Y = (2*Yp + 2/Zp)*eye(n) ...
7    + diag(-1/Zp*ones(n-1,1),1) ...
8    + diag(-1/Zp*ones(n-1,1),-1);
9  Y(n,n) = Yp + 1/Zp + 1/(2*Rz);
10 I = zeros(n,1);
11 I(1) = U0/Zp;
12 U = Y\I;
```

```
>> primer_12
>> abs(U)
ans =
  574.6922
  329.2692
  189.3479
  114.0345
   80.2963
   71.3485
```