SIMULACIJA KRETANJA VLAKA

2. Domaća Zadaća iz
„Napajanja Električne Vuče“

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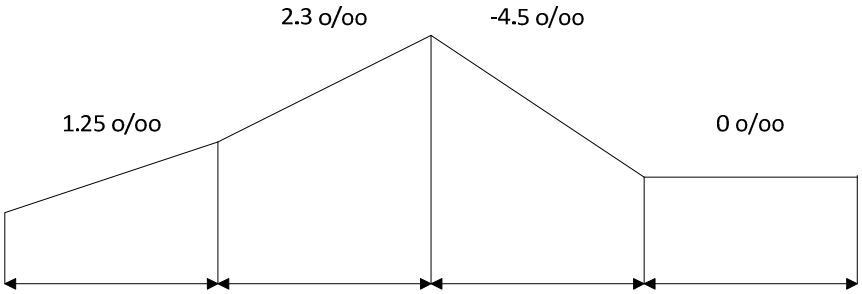
Sadržaj

Podaci potrebni za proračun

Zadani put



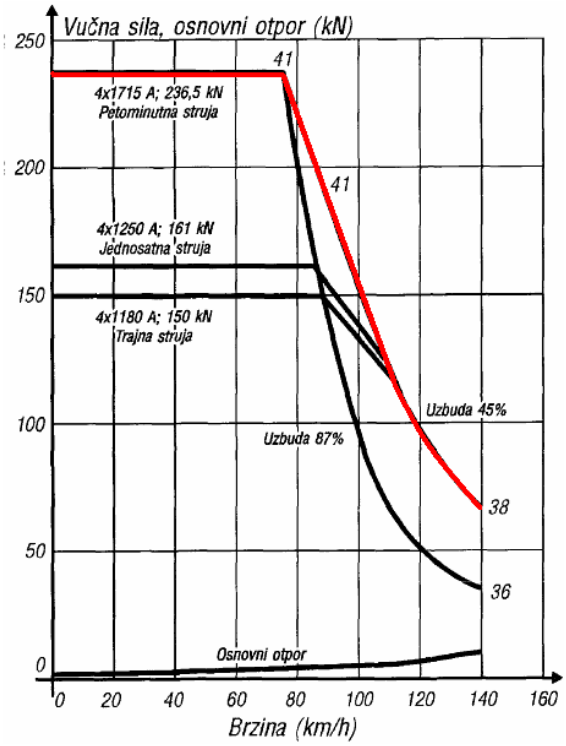
	800 m	1000 m	700 m	1000 m
Radijus krivine	2000 m	3500 m	1200 m	0 m
Planirana brzina	80 km/h	90 km/h	90 km/h	80 km/h

Put na kojem je potrebno provesti proračun sastoji se od četiri dionice duljina 800 m, 1000 m, 700 m i 1000 m kao što je vidljivo na gornjoj slici. Osim duljine pojedinih dionica, podaci koji su nam relevantni kod proračuna su i radijus zavoja (o kojem ovisi sila otpora), nagib dionice (također za račun sile otpora na usponu) te brzina koju vlak treba postići na na svakom pojedinom dijelu puta.

Vučno vozilo

U mojem slučaju radi se o dvije električne lokomotive serije HŽ 1141 koje se napajaju iz kontaktne mreže napona 25 kV i frekvencije 50 Hz. Težina svake lokomotive iznosi 82 t, a ukupna težina vlaka je 1250 t (radi se o teretnom vlaku). Težina i tip vlaka bitni su za odabir koeficijenta k koji se koristi kod računa sile otpora za vučeno vozilo, dakle k=0.057. Korisnost vučnog vozila iznosi: η=0.85, a korisnost električne kočnice η=0.8.

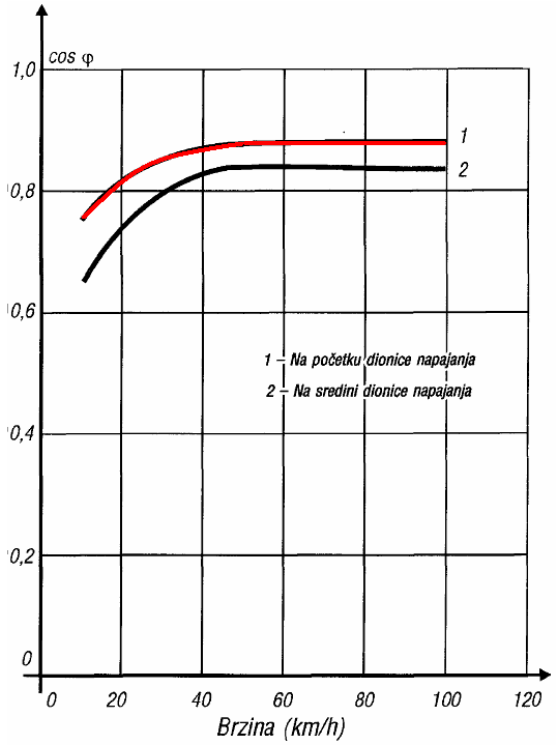
Iz vučnog pasoša vučnog vozila potrebno je očitati koliku vučnu silu može razviti pri određenoj brzini, kod proračuna sam koristio prvu gornju krivulju vučnog pasoša koja odgovara petominutnoj struji iznosa 4x1715 A. Maksimalna sila koju vozilo može razviti iznosi 236.5 kN i vrijedi za brzine do približno 80 km/h.



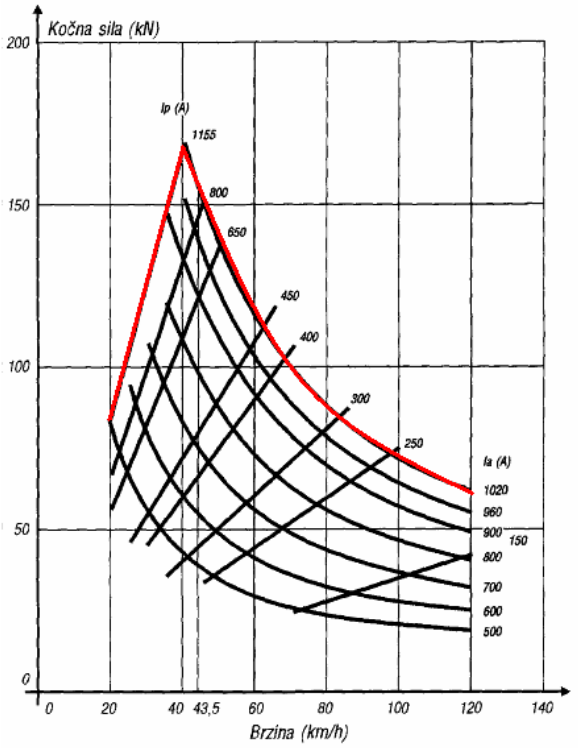
Cosϕ vučnog vozila očitavamo iz krivulje pod brojem 1, a ona se može opisati sljedećim polinomima:

0 – 60 km/h → $-2\cdot10^{-9}\cdot v^5+3.70833\cdot10^{-7}\cdot v^4-0.0000245833\cdot v^3+0.000602917\cdot v^2+0.00167833v+0.646$

60 – 140 km/h → 0.858



Na raspolaganju nam je još i krivulja elektrodinamičkog kočenja, koja se može opisati polinomima:
0-70 km/h → 4.4v
70-160 km/h → $0.0114v^2-3.1486v+283.6$



Proračun

Korak proračuna nam je zadan i iznosi 5 s. Cilj proračuna je u svakom trenutku (odnosno svakih 5 s) dobiti osnovne podatke o kretanju vlaka – prijeđeni put, akceleraciju, brzinu te ono što nas najviše zanima – radnu i jalovu snagu koju vučno vozilo uzima iz mreže ili daje u mrežu (u slučaju da je lokomotiva sposobna za povrat snage). Pretpostavljamo da snaga pomoćnih sustava vlaka iznosi 0.25 MW.

1. dionica

$t = 0 \;\; v = 0 \;\; F_t = 2 \cdot 236.5 \text{ kN} = 473 \text{ kN}$ s=0

$$F_w = \left(\frac{i}{100} + \frac{8000}{R} \cdot 10^{-3} \right) \cdot m_{vl} = \left(\frac{1.25}{100} + \frac{8000}{2000} \cdot 10^{-3} \right) \cdot 1250000 = 20.625 \text{ kN}$$

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 0} \cdot 10 = 541.200 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 25 \text{ kN}$$

$$a = \frac{F_t - \sum F_w}{(1 + \varepsilon) \cdot m_{vl}} = \frac{473 - (20.625 + 25)}{1.07 \cdot 1250} = 0.320 \text{ m/s}^2$$

$$P_m = F_t \cdot v = 0$$

$$P_e = \frac{P_m}{\eta} + P_{pom} = 0.25 \text{ MW} \;\; Q_e = P_e \cdot \tan(\arccos \varphi_{pom}) = 0.5 \cdot \tan(\arccos 0.9) = 0.121 \text{ MVAr}$$

$t = 5s \;\; v = 5.76$ km/h $F_t = 473$ kN s=4 m

$F_w = 20.625$ kN

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 5.76} \cdot 10 = 511.725 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 25.228 \text{ kN}$$

$$a = \frac{F_t - \sum F_w}{(1 + \varepsilon) \cdot m_{vl}} = \frac{473 - (20.625 + 25.228)}{1.07 \cdot 1250} = 0.319 \text{ m/s}^2$$

$$P_m = F_t \cdot v = 0.757 \text{ MW}$$

$$P_e = \frac{P_m}{\eta} + P_{pom} = 1.140 \text{ MW} \;\; Q_e = 1.259 \text{ MVAr}$$

t (s)	a (m/s^2)	v (km/h)	s (m)	P_e (MW)	Q_e (MW)
10	0.319	11.502	15.988	2.028	1.990
15	0.309	17.244	35.950	2.851	2.454
20	0.293	22.806	63.763	3.534	2.704
25	0.278	28.080	99.100	4.128	2.882
30	0.264	33.084	141.575	4.647	3.047
35	0.252	37.836	190.825	5.105	3.218
40	0.241	42.372	246.525	5.514	3.394
45	0.230	46.710	308.388	5.881	3.566
50	0.221	50.850	376.138	6.212	3.728
55	0.212	54.828	449.525	6.513	3.885
60	0.203	58.644	528.325	6.788	4.051
65	0.195	62.298	612.313	7.039	4.214
70	0.188	65.808	701.275	7.270	4.352
75	0.180	69.192	795.025	7.483	4.480

Prelazak na 2. dionicu računamo na sljedeći način:

- preostali put do kraja 1. dionice: $s = 800 - 795.025 = 4.975$ m

$$s = v \cdot t + \frac{a \cdot t^2}{2} \Rightarrow t = 0.259 \text{ s}$$

$t = 75.259$ s $\quad v = 69.36$ km/h $\quad F_t = 473$ kN $\quad s = 800$ m

$$F_w = \left(\frac{i}{100} + \frac{8000}{R} \cdot 10^{-3} \right) \cdot m_{vl} = \left(\frac{2.3}{100} + \frac{8000}{3500} \cdot 10^{-3} \right) \cdot 1250000 = 31.607 \text{ kN}$$

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 69.36} \cdot 10 = 319.556 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 58.067 \text{ kN}$$

$$a = \frac{F_t - \sum F_w}{(1 + \varepsilon) \cdot m_{vl}} = \frac{319.556 - (31.607 + 58.067)}{1.07 \cdot 1250} = 0.172 \text{ m/s}^2$$

$$P_m = F_t \cdot v = 6.157 \text{ MW}$$

$$P_e = \frac{P_m}{\eta} + P_{pom} = 7.493 \text{ MW} \quad Q_e = P_e \cdot \tan(\arccos \varphi) = 7.743 \cdot \tan(\arccos 0.858) = 4.486 \text{ MVAr}$$

2. dionica

t (s)	a (m/s^2)	v (km/h)	s (m)	P_e (MW)	Q_e (MW)
75.259	0.172	69.360	800.000	7.493	4.486
80.000	0.166	72.296	893.286	7.671	4.592
85.000	0.159	75.284	995.772	7.846	4.697
90.000	0.153	78.146	1102.321	8.008	4.794
95.000	0.148	80.900	1212.769	8.159	4.885
100.000	0.142	83.564	1326.980	8.301	4.970
105.000	0.137	86.120	1444.817	8.434	5.049
110.000	0.132	88.586	1566.140	8.558	5.123
112.976	0.000	90.000	1640.215	3.552	2.127
115.000	0.000	90.000	1690.825	3.552	2.127

S obzirom da je maksimalna dozvoljena brzina na 2. dionici 90 km/h, u trenutku t=112.976 s vlak treba prestati ubrzavati i do kraja dionice voziti konstantnom brzinom od 90 km/h.

$$s = v \cdot t + \frac{a \cdot t^2}{2} \Rightarrow t = 0.259 \text{ s}$$

$$t = 112.976 \text{ s} \quad v = 90 \text{ km/h} \quad F_t = 112.283 \text{ kN} \quad s = 1640.215 \text{ m}$$

$$F_w = \left(\frac{i}{100} + \frac{8000}{R} \cdot 10^{-3} \right) \cdot m_{vl} = \left(\frac{2.3}{100} + \frac{8000}{3500} \cdot 10^{-3} \right) \cdot 1250000 = 31.607 \text{ kN}$$

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 69.36} \cdot 10 = 284.842 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 80.676 \text{ kN}$$

$$a = \frac{F_t - \sum F_w}{(1 + \varepsilon) \cdot m_{vl}} = 0 \text{ m/s}^2 \Rightarrow F_t = \sum F_w = F_w + F_p = 112.283 \text{ kN}$$

$$P_m = F_t \cdot v = 2.807 \text{ MW}$$

$$P_e = \frac{P_m}{\eta} + P_{pom} = 3.552 \text{ MW} \quad Q_e = 2.127 \text{ MVAr}$$

Nakon toga računamo prelazak na 3. dionicu:

$$s = v \cdot t + \frac{a \cdot t^2}{2} \Rightarrow t = 4.367 \text{ s}$$

$$t = 119.367 \text{ s} \quad v = 90 \text{ km/h} \quad F_t = 32.759 \text{ kN} \quad s = 1800 \text{ m}$$

$$F_w = \left(\frac{i}{100} + \frac{8000}{R} \cdot 10^{-3} \right) \cdot m_{vl} = \left(\frac{-4.5}{100} + \frac{8000}{1200} \cdot 10^{-3} \right) \cdot 1250000 = -47.917 \text{ kN}$$

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 69.36} \cdot 10 = 284.842 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 80.676 \text{ kN}$$

$$a = \frac{F_t - \sum F_w}{(1 + \varepsilon) \cdot m_{vl}} = 0 \text{ m/s}^2 \Rightarrow F_t = \sum F_w = F_w + F_p = 32.759 \text{ kN}$$

$$P_m = F_t \cdot v = 0.819 \text{ MW}$$

$$P_e = \frac{P_m}{\eta} + P_{pom} = 1.214 \text{ MW} \quad Q_e = 0.726 \text{ MVAr}$$

3. dionica

t (s)	a (m/s^2)	v (km/h)	s (m)	P_e (MW)	Q_e (MW)
119.367	0.000	90.000	1800.000	1.214	0.726
120.000	0.000	90.000	1815.825	1.214	0.726
125.000	0.000	90.000	1940.825	1.214	0.726
130.000	0.000	90.000	2065.825	1.214	0.726
135.000	0.000	90.000	2190.825	1.214	0.726
140.000	0.000	90.000	2315.825	1.214	0.726
142.120	-0.500	90.000	2368.817	-3.453	-2.067
145.000	-0.500	84.816	2438.743	-3.465	-2.074

Prije kraja 3. dionice vlak treba započeti kočenje da bi do početka 4. dionice smanjio brzinu na dozvoljenih 80 km/h:

$a = -0.5 \text{ m/s}^2 \Rightarrow$ iznos akceleracije kod kočenja

$s = v \cdot t + \frac{a \cdot t^2}{2} = 131.183 \text{ m} \Rightarrow$ toliko je vlaku potrebno za smanjivanje brzine na 80 km/h

$s_p = 2368.817 \text{ m} \quad t = 142.120 \text{ s} \Rightarrow$ početak kočenja

$t = 142.120$ s $v = 90$ km/h $F_t = -635.991$ kN $s = 2368.817$ m

$$F_w = \left(\frac{i}{100} + \frac{8000}{R} \cdot 10^{-3} \right) \cdot m_{vl} = \left(\frac{-4.5}{100} + \frac{8000}{1200} \cdot 10^{-3} \right) \cdot 1250000 = -47.917 \text{ kN}$$

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 69.36} \cdot 10 = 284.842 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 80.676 \text{ kN}$$

$$a = -0.5 \frac{m}{s^2}$$

$$P_m = F_t \cdot v = -15.900 \text{ MW}$$

$P_e = 2 \cdot P_{ek} \cdot \eta_k + P_{pom} = -3.453$ MW $Q_e = -2.067$ MVAr

Prelazak na 4. dionicu:

$t = 147.676$ s $v = 80$ km/h $F_t = 68.991$ kN $s = 2500$ m

$$F_w = 0$$

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 80} \cdot 10 = 300.667 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 68.991 \text{ kN}$$

$$a = 0 \frac{m}{s^2} \Rightarrow F_t = \sum F_w = F_w + F_p = 68.991 \text{ kN}$$

$$P_m = F_t \cdot v = 1.533 \text{ MW}$$

$$P_e = \frac{P_m}{\eta} + P_{pom} = 2.054 \text{ MW} \quad Q_e = 1.229 \text{ MVAr}$$

4. dionica

t (s)	a (m/s^2)	v (km/h)	s (m)	P_e (MW)	Q_e (MW)
147.676	0.000	80.000	2500.000	2.054	1.229
150.000	0.000	80.000	2551.644	2.054	1.229
155.000	0.000	80.000	2662.755	2.054	1.229
160.000	0.000	80.000	2773.866	2.054	1.229
165.000	0.000	80.000	2884.977	2.054	1.229
170.000	0.000	80.000	2996.088	2.054	1.229
170.454	-0.500	80.000	3006.173	-3.472	-2.078
175.000	-0.500	71.817	3102.029	-3.461	-2.072
180.000	-0.500	62.817	3195.525	-3.402	-2.036
185.000	-0.500	53.817	3276.521	-3.270	-1.953
190.000	-0.500	44.817	3345.017	-3.044	-1.857
195.000	-0.500	35.817	3401.012	-2.702	-1.728
200.000	-0.500	26.817	3444.508	-2.221	-1.582
205.000	-0.500	17.817	3475.504	-1.580	-1.343
210.000	-0.500	8.817	3494.000	-0.756	-0.787
214.898	0.000	0	3500.000	0.250	0.121

Na kraju je još potrebno izračunati u kojem trenutku vlak treba započeti s kočenjem da bi se do kraja 4. dionice stigao zaustaviti, tj. smanjiti brzinu na 0 km/h:

$$a = -0.5 \text{ m/s}^2 \quad \Delta v = -22.222 \text{ km/h} \Rightarrow \Delta t = \frac{\Delta v}{a} = 44.444 \text{ s}$$

$$s = v \cdot t + \frac{a \cdot t^2}{2} = 493.827 \text{ m} \Rightarrow \text{udaljenost potrebna za zaustavljanje}$$

$$s_p = 1000 - 493.827 = 506.173 \text{ m} \Rightarrow \text{početak kočenja}$$

$$t = 170.454 \text{ s} \quad v = 80 \text{ km/h} \quad F_t = -599.759 \text{ kN} \quad s = 3006.173 \text{ m}$$

$$F_w = 0$$

$$F_{adh} = m_{lok} \cdot \frac{\Psi_0}{1 + 0.01v} \cdot 10 = 2 \cdot 82000 \cdot \frac{0.33}{1 + 0.01 \cdot 80} \cdot 10 = 300.667 \text{ kN}$$

$$F_p = m_{lok} \cdot \left(20 + \frac{v^2}{240} \right) \cdot 10^{-3} + (m_{vl} - m_{lok}) \cdot \left(20 + \frac{v^2}{10} \cdot k \right) \cdot 10^{-3} = 68.991 \text{ kN}$$

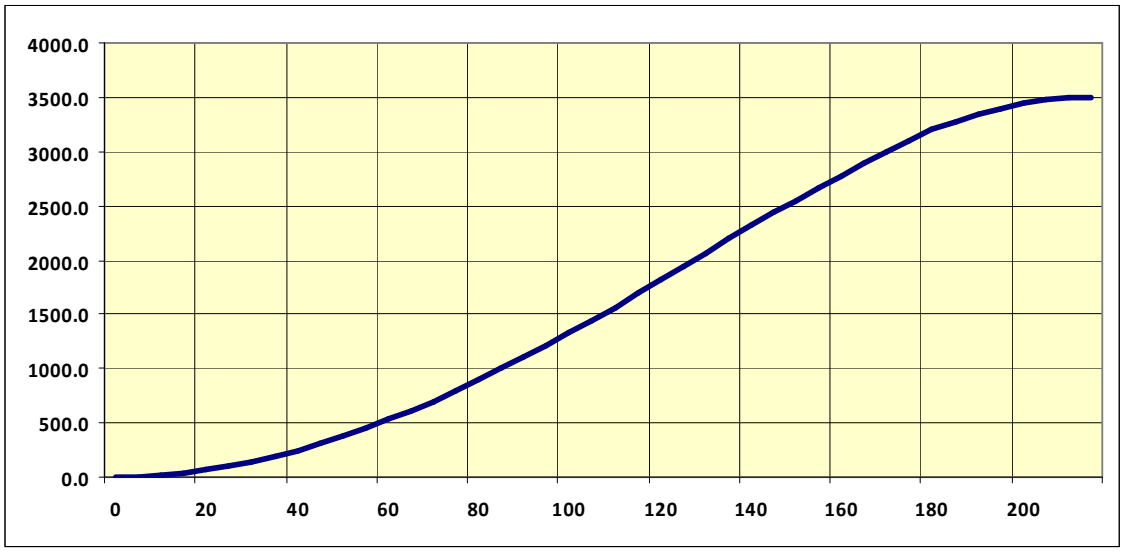
$$a = -0.5 \text{ m/s}^2$$

$$P_m = F_t \cdot v = -13.328 \text{ MW}$$

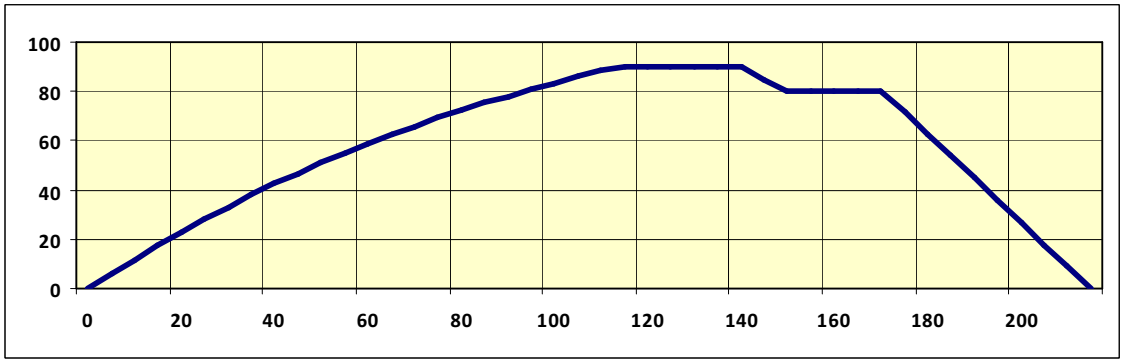
$$P_e = 2 \cdot P_{ek} \cdot \eta_k + P_{pom} = -3.472 \text{ MW} \quad Q_e = -2.078 \text{ MVAr}$$

Grafički prikaz rezultata

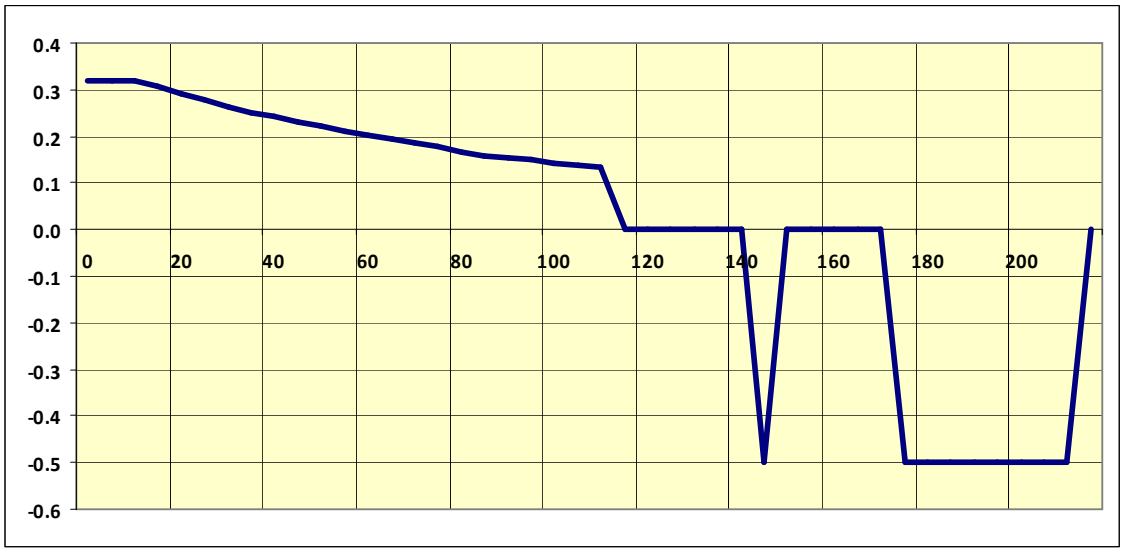
s-t



v-t



a-t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0.2
0.1
0.0
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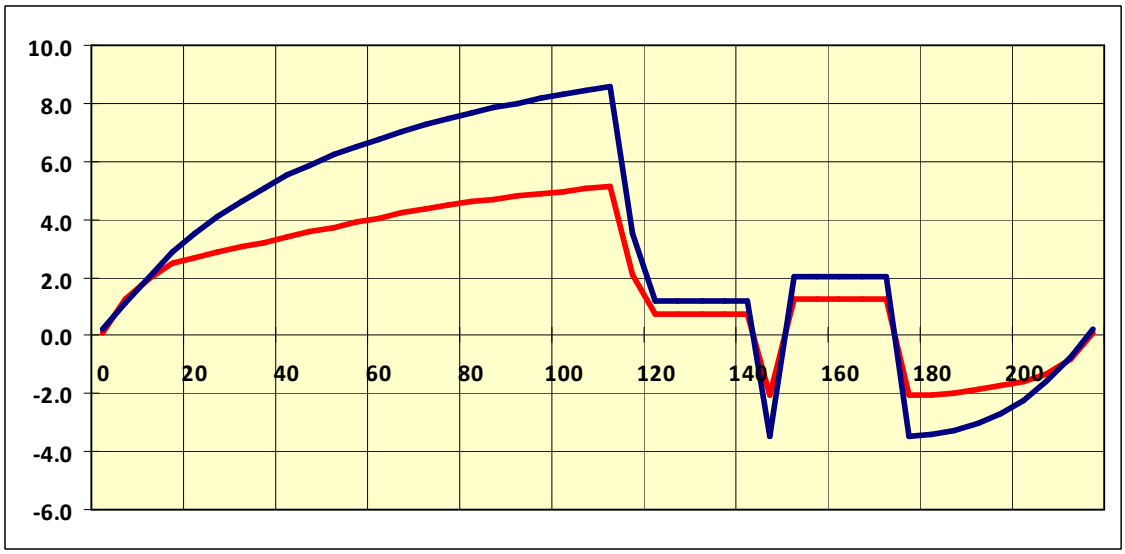
-0.2
-0.3
-0.4
-0.5
-0.6
0
20
40
60
80
100
120
140
160
180
200

P-t, Q-t


10.0
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4.0
2.0
0.0
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-6.0
0
20
40
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80
100
120
140
160
180
200