TERMIČKA ANALIZA UKOPANIH VISOKONAPONSKIH KABELA
THERMAL ANALYSIS OF BURIED HIGH-VOLTAGE CABLES

Bojan Trkulja – Željko Štih – Sead Berberović, Zagreb, Hrvatska

U okviru ovog rada provedena je spregnuta elektromagnetsko – termička analiza trofaznog sustava sastavljenog od tri jednožilna kabela u konfiguraciji delta. Sustav kabela analizira se u termički stacionarnom i nestacionarnom stanju, uzimajući u obzir nelinearnost provoda topline u tlu u okolini kabela. Složeni model prijenosa topline u tlu, uzrokovan isušivanjem tla u okolini kabela izveden je primjenom dvije zone različitih toplinskih vodljivosti.

The present work includes the coupled electromagnetic/thermal analysis of a three-phase system composed of three single-core cables in trefoil configuration. The cable system is analyzed in thermally stationary and non-stationary state, taking into account the non-linearity of heat conduction in the soil surrounding the cable. The complex model of heat transfer in soil, caused by soil drying in the cable's surrounding, has been made by applying two zones of different heat conductions.

Ključne riječi: termička analiza; visokonaponski kabeli
Keywords: thermal analysis; high-voltage cables


ANMA-25
003456
FEET

1 UVOD

Ukopani visokonaponski kabeli često se koriste u prijenosu električne energije u gusto naseljenim područjima. Kabeli se u pogonu zagrijavaju, a toplina se prenosi u okolno tlo, što dovodi do porasta temperature unutar kabela i u njihovoj okolini. Porast temperature treba zadržati unutar propisanih vrijednosti kako bi se osigurala pouzdanost opskrbe energijom i produžio životni vijek izolacije kabela. Imajući u vidu visoku cijenu kabelske infrastrukture, potrebno je odrediti maksimalnu struju opterećenja kabela, što osigurava optimalnu iskoristivost u prijenosu energije. Proračun maksimalnog opterećenja značajan je za termički stacionarna i nestacionarna stanja.

Različiti se pristupi primjenjuju u proračunu strujnog opterećenja kabela. Klasične procedure za proračun termičkih svojstava kabela temeljene su na konstantnim vrijednostima vodljivosti tla i rješenju jednadžbe prijenosa topline. Najjednostavniji slučaj koji predviđa HRN IEC 60287 [1] je opterećenje kabela neprekidnom strujom konstantne vrijednosti, koja je definirana kao maksimalna dozvoljena trajna struja od strane proizvođača. Za takav proračun tlo se može smatrati uniformnim i toplinska mu je vodljivost konstantna. Struja se u uvjetima preopterećenja može izračunati prema HRN IEC 60853 [2]. Toplinska vodljivost tla je temperaturno ovisna. U razvoju točnijeg modela potrebno je uzeti u obzir temperaturnu promjenjivost toplinske vodljivosti tla.

U okviru ovog rada promjenjiva toplinska vodljivost modelirana je s dva temperaturna područja. Za vlažno tlo se pretpostavlja da ima jednoliku toplinsku vodljivost. Za granicu vlažnog i suhog tla uzima se izoterma za koju je temperatura 30 °C viša od temperature okoline [3]. Termičke prilike u okolini tri jednofazna 110 kV kabela računaju se primjenom metode konačnih elemenata koristeći simultano programske pakete MagNet i ThermNet [4], pri čemu je spregnut elektromagnetski proračun u frekvencijskoj domeni i termički proračun u vremenskoj domeni.

Analiza je za stacionarno stanje provedena za dva modela kabela. U pojednostavljenom modelu je bakreni ekran kabela modeliran cilindrom jednake površine poprečnog presjeka. U detaljnom je modelu uzeta u obzir stvarna geometrija bakrenih žica u ekranu.

U analizi kabela u termički nestacionarnom stanju proračunate su struje preopterećenja za temperaturno promjenjivi i konstantni model toplinske vodljivosti tla. Proračun je proveden za različite struje preopterećenja i struje prethodnog opterećenja kabela. Rezultati su uspoređeni s vrijedno-

1 INTRODUCTION

The buried high-voltage cables are often used for electricity transmission in densely populated areas. Cables in operation warm up and heat spreads to the surrounding soil, which leads to temperature rise inside and around the cables. Temperature increase should be kept within certain prescribed limits so as to ensure power supply reliability and to prolong the life-cycle of cable insulation. In view of the costly cabling infrastructure, it is necessary to determine maximum cable current load to ensure optimum power transmission usability. The maximum load calculation is important for thermally stationary and non-stationary states.

Different methods are applied in calculating the cable current load. Classical procedures for calculating the thermal properties of cables are based on constant values of soil conductivity and the result of the heat transfer equation. The simplest case envisaged by HRN IEC 60287 [1] is cable loading by uninterrupted current of constant value, defined as maximum constant current allowed by the manufacturer. For such a calculation soil can be considered uniform and its thermal conductivity is constant. Under overload conditions, current can be calculated according to HRN IEC 60853 [2]. The thermal conductivity of soil is temperature-dependent. In developing a more accurate model it is necessary to take into account the temperature variability of the thermal conductivity of soil.

In this work the variable thermal conductivity is modeled with a two-zone model. For damp soil a uniform thermal conductivity is assumed. For the boundary between damp and dry soil an isotherm is taken for which temperature is by 30 °C higher than the ambient temperature [3]. Thermal conditions in an environment of three 110 kV single-phase cables are calculated by the finite element method simultaneously using the coupled MagNet and ThermNet software packages [4], where the coupled electromagnetic calculation is in the frequency domain and thermal calculation in the time domain.

The analysis for the stationary state was made for two cable models. In the simplified model the copper screen of the cable was modeled by a cylinder of equal cross-section surface. In the detailed model the real geometry of copper wires in the screen was taken into account.

In analyzing the cable in the thermally non-stationary state the overload currents were calculated for a temperature variable and a constant model of the thermal conductivity of soil. The calculation was carried out for different overload currents and prior overload currents. The results were compastima dobivenima prema HRN IEC 60853 [2].

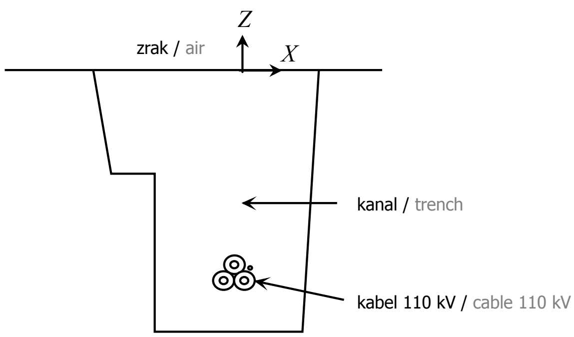
2 ANALIZA KABELA U STACIONARNOM STANJU

Analiza termičkih prilika za sustav tri jednofazna kabela 110 kV u stacionarnom stanju provedena je za konfiguraciju kabela prema slici 1.

red with the values obtained according to HRN IEC 60853 [2].

2 ANALYZING A CABLE IN THE STATIONARY STATE

An analysis of thermal conditions for a system of three 110 kV single-phase cables in the stationary state was made for a cable configuration shown in Figure 1.



Slika 1 — Tri jednožilna kabela u konfiguraciji delta u kanalu
Figure 1 — Three single-core cables in a trench

Poprečni presjek jednofaznog kabela ilustriran je slikom 2.

The cross-section of a single-core cable is shown in Figure 2.

Slika 2 — Poprečni presjek jednofaznog visokonaponskog kabela
Figure 2 — Cross-section of single-core cable

Zaštitno uže u okolini kabela modelirano je bakrenom žicom poprečnog presjeka 185 mm2. Metalni ekran kabela, sastavljen od koncentričnih bakrenih žica modeliran je na dva načina:

2.1 Pojednostavljeni model

Za ovaj model metalni je ekran nadomješten bakrenim cilindrom jednakog poprečnog presjeka. Presjek aluminijske jezgre kabela je 1 000 mm2.

The protection line in the surrounding of the cable is modeled by a 185 mm2 cross-section copper wire. The metal screen of the cable, made up of concentric copper wires, is modeled in two ways:

2.1 A simplified model

For this model the metal screen is substituted by a copper cylinder of equal cross-section. The cable core cross-section is 1 000 mm2.

Najjednostavniji slučaj koji predviđa HRN IEC 60287 [1] je opterećenje kabela neprekidnom strujom konstantne vrijednosti, koja je definirana kao maksimalna dozvoljena trajna struja od strane proizvođača $I_n = 798$ A, što je dobiveno izrazom:

The simplest case according to HRN IEC 60287 [1] is cable overloading by uninterrupted current of constant value, defined as maximum constant current allowed by the manufacturer, $I_n = 798$ A, obtained by the expression:

$$I_n = \sqrt{\frac{\Delta\theta - W_d\left[0{,}5T_1 + n\left(T_2 + T_3 + T_4\right)\right]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)}} = 798 \text{ A}. \quad (1)$$

Pri tom je:

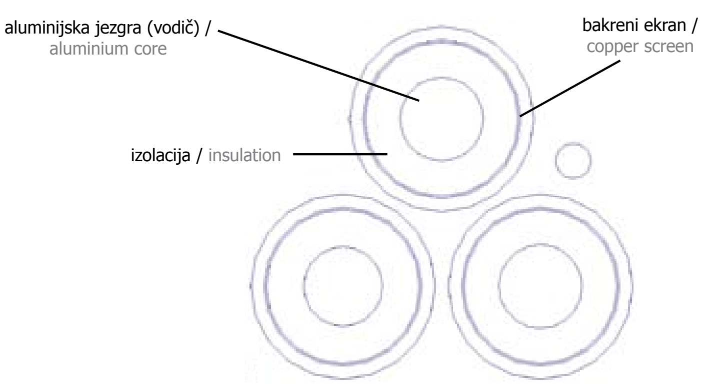
- $\Delta\grave{e}$ – porast temperature vodiča iznad temperature okoline 20 °C,
- R – električni otpor vodiča [Ω/m],
- T_1, T_2 i T_3 – termički otpori slojeva vodiča po jedinici duljine [K m/W],
- T_4 – termički otpor površine kabela prema okolini po jedinici duljine [K m/W],
- W_d – dielektrički gubici po jedinici duljine [W/m],
- n – broj vodiča protjecanih strujom u jednom kabelu
- λ_1 – omjer gubitaka u metalnom ekranu kabela i ukupnih gubitaka u vodičima,
- λ_2 – omjer gubitaka u metalnoj armaturi i ukupnih gubitaka u vodičima.

Za $I_n = 798$ A stacionarna temperatura površine aluminijskog vodiča ne bi trebala prelaziti vrijednost 90 °C prema HRN IEC 60287 [1]. Kabeli su ukopani na dubini 1,2 m. Izolacijski materijal kabela je XLPE . Pojednostavljeni model kabela u rasporedu delta prikazan je slikom 3.

where:

- $\Delta\grave{e}$ – conductor temperature increase above ambient temperature 20 °C,
- R – electrical resistance [Ω/m],
- T_1, T_2 i T_3 – thermal resistances of conductor layers by unit of length [K m/W],
- T_4 – thermal resistance of cable surface against the environment by unit of length [K m/W],
- W_d – dielectric losses by unit of length [W/m],
- n – number of current-flown conductors in one cable
- λ_1 – ratio between losses in the metal screen and total losses in the conductors
- λ_2 – ratio between losses in the metal armor and total losses in the conductors

For $I_n = 798$ A the stationary temperature of the aluminium conductor surface should not exceed 90 °C according to HRN IEC 60287 [1]. The cables are buried at the depth of 1,2 m. Cable insulation material is XLPE. The simplified cable model in trefoil configuration is shown in Figure 3.

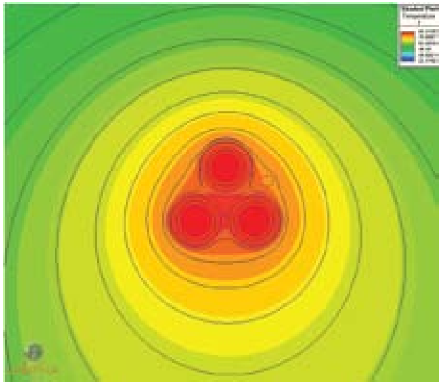


Slika 3 — Pojednostavljeni model kabela u rasporedu delta

Figure 3 — Simplified model of the cable system

Proračun temperature unutar kabela i u njegovoj okolini prikazan je slikom 4.

The calculation of temperature within the cable and in its surrounding is shown in Figure 4.



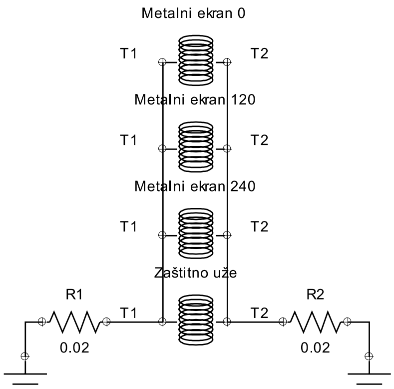
Slika 4 — Prikaz temperaturnog polja u okolini kabela
Figure 4 — Temperature field plot for a simplified model

Metalni ekrani kabela, kao i zaštitno uže uzemljeni su preko otpora uzemljenja 20 mΩ na oba kraja kabela. Električni krug metalnih ekrana i zaštitnog užeta prikazan je slikom 5.

Inducirane struje u metalnim ekranima i zaštitnom užetu su temperaturno promjenjive zbog promjenjive vrijednosti električne otpornosti bakra. Za električni otpor bakrenih ekrana i zaštitnog užeta pretpostavljeno je da je linearno promjenjiv s temperaturom.

The metal screens of cables, as well as the protection line, are grounded via 20 mΩ grounding resistance at both cable ends. The electric circuit of metal screens and the protection line are shown in Figure 5.

The induced currents in the metal screens and the protection line are temperature-variable due to the variable resistance values of copper. The electrical resistance of the copper screens and the protection line is assumed to be linearly variable with temperature.



Slika 5 — Električni krug metalnih ekrana i zaštitnog užeta
Figure 5 — Electric circuit of copper screens and protection line

2.2 Detaljni model

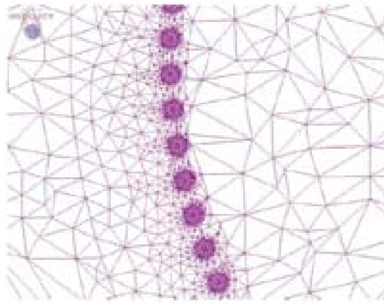
U ovom je modelu primijenjena točna geometrija metalnog ekrana. Metalni je ekran modeliran s 97 žica promjera 1,1 mm.

Detalj mreže u metodi konačnih elemenata prikazan je slikom 6.

2.2 Detailed model

In this model the exact metal screen geometry is applied. The metal screen is modeled with 97 wires, diameter 1,1 mm.

A detail of the mesh in the finite element method is shown in Figure 6.



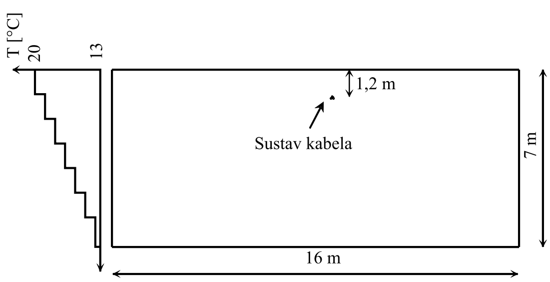
Slika 6 — Detalj mreže
Figure 6 — Detail of mesh

Kao i u jednostavnijem modelu sve su žice u metalnim ekranima zajedno sa zaštitnim užetom na krajevima kabela kratko spojene i uzemljene preko 20 mΩ.

Termički su rubni uvjeti ilustrirani slikom 7. Za temperaturu tla pretpostavlja se linearni porast od 13 °C na dubini 7 m do temperature okoline 20 °C na površini zemlje. Linearni je porast približen po dijelovima stalnim iznosima prema slici 7. Na površini zemlje je za koeficijent prijenosa topline uzeta vrijednost 11 W/(m2 K) [5].

As in a simpler model, all wires in metal screens together with the protection line are short-circuited at cable ends and grounded via 20 mΩ.

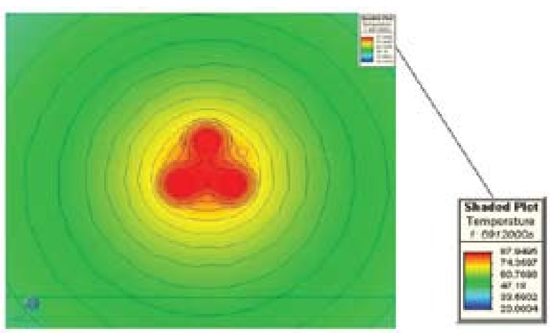
The thermal boundary conditions are shown in Figure 7. For soil temperature a linear increase from 13 °C at the depth of 7 m to ambient temperature of 20 °C on the ground surface is assumed. The linear increase is approximated by parts to constant values according to Figure 7. For the ground surface, the value 11 W/(m2 K) [5] is taken for the heat transfer coefficient.



Slika 7 — Termički rubni uvjeti
Figure 7 — Thermal boundary conditions

Distribucija temperature u okolini kabela prikazana je slikom 8.

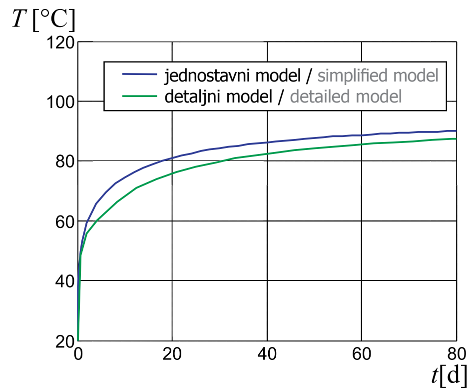
Temperature distribution in the cable surrounding is shown in Figure 8.



Slika 8 — Distribucija temperature u okolici kabela
Figure 8 — Temperature field distribution for a detailed model

Temperaturni tranzijent za pojednostavljeni i detaljni model prikazan je slikom 9.

Temperature transients for simplified and detailed models are shown in Figure 9.



Slika 9 — Temperaturni tranzijent za pojednostavljeni model i detaljni model
Figure 9 — Temperature transients for simplified and detail model

Razlika između stacionarne temperature za pojednostavljeni model i detaljni model je manje od 3 °C. Budući da je razlika u proračunu temperature pojednostavljenog i detaljnog modela mala, pojednostavljeni model može se primjenjivati u većini slučajeva. Prema tome, analiza u termički nestacionarnom stanju bit će provedena uz primjenu pojednostavljenog modela kabela.

The stationary temperature difference between the simplified and the detail model is less than 3 °C. Considering such a small difference in temperature calculation between the simplified and the detail model, the simplified model can be applied in most cases. Therefore, the analysis in the thermally non-stationary state will be made by using the simplified cable model.

3 PRORAČUN TERMIČKIH PRILIKA PREOPTEREĆENOG KABELA

3 CALCULATION OF THERMAL CONDITIONS OF AN OVERLOADED CABLE

Preopterećenje kabela posebno je interesantno u prijenosu električne energije. Trajanje dopuštenog preopterećenja ovisno je o prethodnom opterećenju kabela i struji preopterećenja. U ovom se radu analizira dopušteno preopterećenje za različite struje prethodnog opterećenja i preopterećenja bazirano na porastu temperature unutar kabela.

Prema [2] maksimalna struja preopterećenja može se računati prema jednadžbi:

Cable overload is particularly interesting when it comes to power transmission. The duration of overload depends on the prior load and the overload current. The present work analyzes the allowed overload for different currents of prior load and overload based on temperature increase within the cable.

According to [2], maximum overload current can be calculated by means of the following equation:

$$I_2 = I_n \sqrt{\frac{h_1^2 \cdot R_1}{R_{max}} + \frac{\frac{R_R}{R_{max}}\left(r - h_1^2 \frac{R_1}{R_R}\right)}{\frac{\theta_R(t)}{\theta_R(\infty)}}}, \qquad (2)$$

gdje su:

I_n – maksimalna dopuštena konstantna struja,
I_1 – struja koja prethodi preopterećenju,
I_2 – struja preopterećenja,
R_1 – otpor vodiča prije preopterećenja [Ω/m],
R_R – otpor vodiča pri maksimalnoj dopuštenoj konstantnoj struji [Ω/m],
R_{max} – otpor vodiča na kraju perioda preopterećenja [Ω/m].
h_1 – omjer struje koja prethodi preopterećenju i maksimalne dopuštene konstantne struje

Rezultati proračuna za struje prethodnog opterećenja od 40 % I_n , 60 % I_n i 80 % I_n prikazani su u tablici 1. Dopuštena su preopterećenja pri kojima temperatura ne smije prelaziti 105 °C, na čemu su bazirani dobiveni rezultati.

Proračun dopustivih struja preopterećenja bit će proveden za konstantne i promjenjive vrijednosti toplinske vodljivosti tla.

3.1 Proračun baziran na konstantnim vrijednostima toplinske vodljivosti tla

U ovom se proračunu pretpostavlja temperaturno nepromjenjiva vrijednost toplinske vodljivosti tla. Za toplinsku je vodljivost tla pretpostavljen iznos 1 W/(K m).
Rezultati za različite prethodne struje opterećenja prikazani su slikama 10, 11 i 12.

where:

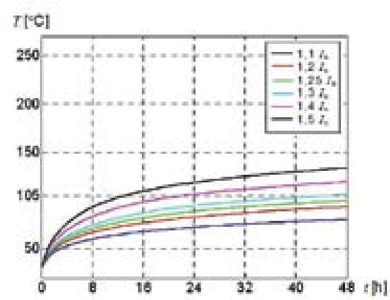
I_n – maximum allowed constant current,
I_1 – current prior to overload,
I_2 – overload current,
R_1 – conductor resistance prior to overload [Ω/m],
R_R – conductor resistance at maximum allowed constant current [Ω/m],
R_{max} – conductor resistance at the end of the overload period [Ω/m],
h_1 – ratio between current prior to overload and maximum allowed constant current.

Calculation results for prior load currents 40 % I_n , 60 % I_n and 80 % I_n are shown in Table 1. Overloads are allowed where temperature may not exceed 105 °C, on which the obtained results are based.

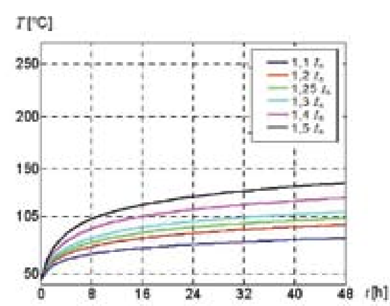
The calculation of permissible overload currents will be carried out for constant and variable values of the thermal conductivity of soil.

3.1 Calculation based on constant values of the thermal conductivity of soil

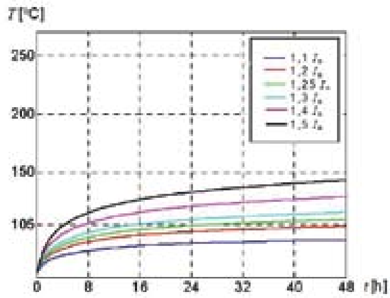
In this calculation a constant temperature value of the thermal conductivity of soil is assumed. The amount assumed for the thermal conductivity of soil is 1 W/(K m).
The results for different prior overload currents are shown in Figures 10, 11 and 12.



Slika 10 — Temperaturni tranzijent za prethodno opterećenje 40 % I_n
Figure 10 — Temperature transient for prior load 40 % I_n



Slika 11 — Temperaturni tranzijent za prethodno opterećenje 60 % I_n
Figure 11 — Temperature transient for prior load 60 % I_n



Slika 12 — Temperaturni tranzijent za prethodno opterećenje 80 % I_n
Figure 12 — Temperature transient for prior load 80 % I_n

Tablica 1 – Vrijeme potrebno da temperatura vodiča dosegne 105 °C
Table 1 – Time required for temperature to reach 105 °C

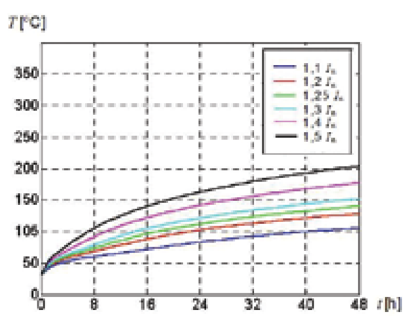
Prethodno opterećenje / Prior load	Trajanje preopterećenja / Duration of overload [h]					
	1,1 % I_n	1,2 % I_n	1,25 % I_n	1,3 % I_n	1,4 % I_n	1,5 % I_n
40 % I_n	536	136	79	50	22	12
60 % I_n	517	109	60	36	16	8
80 % I_n	458	62	31	18	7	4

3.2 Proračun baziran na promjenjivoj toplinskoj vodljivosti tla

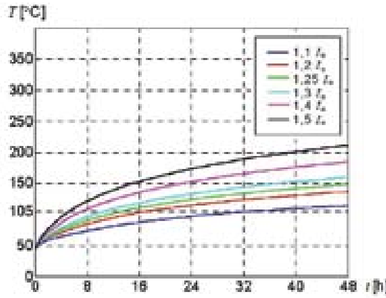
Toplinska vodljivost tla modelirana je s dvije zone. Za temperature ispod kritične izoterme na 50 °C za toplinsku vodljivost tla se pretpostavlja vrijednost 1 W/(K m). Za temperature iznad 50 °C pretpostavlja se toplinska vodljivost 0,33 W/(K m) [3]. Rezultati proračuna prikazani su na slikama 13, 14 i 15.

3.2 Calculation based on variable thermal conductivity of soil

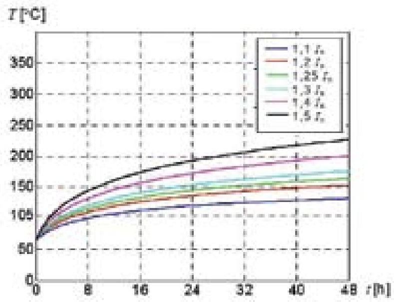
The thermal conductivity of soil is modeled with two zones. For temperatures below the critical isotherm at 50 °C, the value 1 W/(K m) is assumed for the thermal conductivity of soil. For temperatures above 50 °C the thermal conductivity of 0,33 W/(K m) [3] is assumed. The calculation results are shown in Figures 13, 14 and 15.



Slika 13 — Temperaturni tranzijent za prethodno opterećenje 40 % I_n
Figure 13 — Temperature transient for prior load 40 % I_n



Slika 14 — Temperaturni tranzijent za prethodno opterećenje 60 % I_n
Figure 14 — Temperature transient for prior load 60 % I_n



Slika 15 — Temperaturni tranzijent za prethodno opterećenje 80 % I_n
Figure 15 — Temperature transient for prior load 80 % I_n

4 ZAKLJUČAK

Zbog visoke cijene ukopanih visokonaponskih kabela iznimno je važno točno proračunati maksimalno dopuštene vrijednosti konstantne struje opterećenja u stacionarnim uvjetima, kao i struje preopterećenja u termički nestacionarnim uvjetima.

Analizirani su pojednostavljeni i detaljni model kabela, a određene su vrijednosti maksimalno dopuštene stacionarne struje, kao i struje preopterećenja za različite vrijednosti struja prethodnog opterećenja, temeljene na porastu temperature unutar kabela.

Razlike u dozvoljenoj temperaturi za pojednostavljeni i detaljni model kabela nisu značajne, tako da pojednostavljeni model može biti primijenjen u većini inženjerskih zadaća. Za točnije proračune detaljni model bi trebao biti primijenjen.

Proračun baziran na konstantnim vrijednostima toplinske vodljivosti tla pokazuje dobro slaganje s vrijednostima dobivenim prema IEC standardima.

4 CONCLUSION

Due to the high prices of buried high-voltage cables it is very important to exactly calculate maximum allowed values of constant load current in stationary conditions, as well as overload current in thermally non-stationary conditions.

The simplified and detailed cable models were analyzed and the values of maximum allowed stationary current determined, and so were overload currents for different values of prior load currents, based on temperature increase inside the cable.

The differences in allowed temperature for both the simplified and the detailed cable model are not significant, so that the simplified model can be applied in dealing with most engineering tasks. For a more accurate calculation the detailed model should be applied.

The calculation based on constant values of the thermal conductivity of soil matches well with the values obtained according to IEC standards.

LITERATURA / REFERENCES

[1] HRN IEC 60287,Električni kabeli : Proračun strujne opteretivosti
[2] HRN IEC 60853, Proračun cikličke vrijednosti struje kable i struje preopterećenja
[3] FREITAS, D.S., PRATA, A.T., DE LIMA, A.J., Thermal Performance of Underground Power Cables with Constant and Cyclic Currents in Presence of Moisture Migration in the Surrounding Soil, IEEE Transactions on Power Delivery, Vol.11, No.3, July 1996
[4] Infolytica MagNet Tutorial, www.infolytica.com
[5] GARRIDO, C., OTERO, A., CIDRAS, J., Theoretical Model to Calculate Steady-State and Transient Ampacity and Temperature in Buried Cables, IEEE Transactions on Power Delivery, Vol..18, No.3, July 2003

Adrese autora:

Dr. sc. **Bojan Trkulja**
bojan.trkulja@fer.hr
Prof. dr. sc. **Željko Štih**
zeljko.stih@fer.hr
Prof. dr. sc. **Sead Baerberović**
sead.berberovic@fer.hr
Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva
Unska 3
10000 Zagreb
Hrvatska

Authors' Adresses:

Bojan Trkulja, PhD
bojan.trkulja@fer.hr
Prof **Željko Štih**, PhD
zeljko.stih@fer.hr
Prof **Sead Baerberović**, PhD
sead.berberovic@fer.hr
University of Zagreb
Faculty of Electrical Engineering and Computing
Unska 3
10000 Zagreb
Croatia

Uredništvo primilo rukopis:
2008-12-23

Prihvaćeno:
2009-01-30

Manuscript received on:
2008-12-23

Accepted on:
2009-01-30