ISSN 1392 – 1215 *ELECTRONICS AND ELECTRICAL ENGINEERING* 2011. No. 9(115)
ELEKTRONIKA IR ELEKTROTECHNIKA

T 190 ELECTRICAL ENGINEERING
ELEKTROS INŽINERIJA

Effect of Climate Change on MV Underground Network Operations in the Future Smart Grid Environment

M. Hashmi, R. J. Millar, M. Lehtonen
Department of Electrical Engineering, Aalto University,
Otakaari 5, 02015, Espoo, Finland, phone: +358 40 1594360, e-mails: murtaza.hashmi@tkk.fi,john.millar@tkk.fi, matti.lehtonen@tkk.fi

S. Hanninen
Department of Energy Systems, VTT Technical Research Centre of Finland, FIN-02044, e-mail: seppo.hanninen@vtt.fi

crossref http://dx.doi.org/10.5755/j01.eee.115.9.743

Introduction

Underground power cables are more expensive to install and maintain than overhead lines. The greater cost of underground installation reflects the high cost of materials, equipment, labour, and time necessary to manufacture and install the cable. The large capital cost investment makes it necessary to use their full capacity. On the other hand, the conductor temperature of a power cable limits its ampacity (maximum allowable current). Also, the operating temperature adversely affects the useful working life of a cable. Excessive conductor temperature may irreversibly damage the cable insulation and jacket.

A successful model was proposed for calculating the ampacity of underground cables by Neher-McGrath in 1957 [1]. The Neher-McGrath Model has been widely accepted for over 40 years. Today, the greater majority of utilities and cable manufacturers have been using the IEC-60287 standard [2]. The analytical modeling of the heat transfer mechanism by IEC-60287 works well in simple cable installations. However, the simplifying assumptions and empirical correlations inherent in the analytical method make solution difficult for installations such as crossing cable ducts, cables on trays, cables near buildings, cable splices, etc. Thus, the standards are not directly applicable for the analysis of complex configurations.

Today's computer technology enables the finite element method (FEM) the capability to solve many of these cases with very complex geometrical configurations. It can solve complex installations in just about any environment and subject to any type of load condition, and can perform transient analysis efficiently. When the cable surrounding is composed of various materials with different thermal resistivities, the IEC-60287 formulation fails to achieve an acceptable result. Therefore, FEM is also powerful and precise in terms of geometrical modeling complexity. Ampacity analysis of cables with FEM has been studied by many researchers [3-5]; however, it becomes tedious to draw a multitude of different models for varying specifications.

This paper deals with current rating calculations performed for 3-phase medium voltage (MV) cross linked polyethylene (XLPE) power cable installations (consisting of 3 single-phase cables) in steady-state conditions using an analytical set of thermal equations. The primary goal is to investigate the possible extreme circumstances due to climate change. A fully transient algorithm that generates and utilises governing exponential equations has already developed for this purpose [6], and this paper uses a steady-state simplification of that algorithm. The analysis is made for different installation configurations under the various Finnish environmental conditions. This investigation will enable electric utilities to revise allowable current ratings to avoid cables damages as well as to ensure safe and reliable distribution of power to the customers. The investments to build new installations can be partially delayed and the better asset management of aged network components can enhance the flexibility of operations required in future smart grids.

Factors affecting thermal resistivity of soil

The permissible current in underground cables depends on the maximum allowable temperature of the cable insulation material. As heat is generated by underground cables, assessment of the thermal resistivity of the soil surrounding the cable is critical to avoid failure of the cables by overheating and to achieve the highest possible current loading. Soils with higher thermal resistance will not dissipate heat as rapidly away from cables as soils with a low thermal resistance [7]. The thermal resistivity of soil is primarily influenced by soil composition, soil density, and the available moisture contents.

Different types of cable installations

The evaluation of thermal properties of the soils that surround underground distribution lines is an important part of the existing design procedures for power cables. The AHXAMK-W 3-core 20 kV XLPE cable is used in this study [8]. The MV cables buried in the following two ways have been considered for ampacity and thermal capacity calculations.

Direct burial installation

The most common method for installing power cables underground is to lay them directly in the soil at a certain depth. The typical installation configurations of a three-phase circuit composed of single-core cables laid directly in the soil are flat and triangular or trefoil types. For ampacity calculations, the cable under investigation is assumed to be buried at a depth of 0.7 m in different environments having trefoil configuration. In this configuration, the cables are touching each other. Separation of the phases improves the heat dissipation process; however, in some cases, this arrangement produces increased power losses [3].

Tube installation

In this arrangement, the cable is laid inside a plastic tube that is often of a corrugated construction to provide a good compromise between mechanical stiffness and light weight. The inside and outside diameters of the tube are assumed to be 0.14 and 0.16 m, respectively. The air interface, and to some extent the heat transfer across the composite section of the tube is still quite challenging to model accurately, being a rather difficult to solve combination of radiation, convection, and conduction [6].

Various installations environmental conditions

The value of thermal resistivity usually used for cable rating is 1 K.m/W. This value seems suitable for most high voltage (HV) installations with a well controlled installation environment, but not necessarily for all MV installations. Due to dried soil, material near MV cables sometimes has a thermal resistivity as high as 5 K.m/W. The critical temperature rise (of the cable surface over ambient) for moisture migration is generally assumed to be 35 °C, however, it has been observed that moisture migration can begin from as low as 10 °C above ambient in sand backfills [9]. If such locations dry out due to high temperatures in the cables or other services, or due to a long-term dry period (such as the dry summers that occurred in Finland in 2002, 2003, and 2006), cable temperatures may run hotter than expected and leave little margin to cope with emergency peaks in loading. The following environmental conditions have been investigated in this paper to demonstrate their effects on the cable current rating:

a. No moisture migration (moist environment);
b. Moisture migration in controlled environment;
c. Moisture migration in uncontrolled environment;
d. Fully dry environment (worst case)

In the controlled environment, the cable is installed in backfill (usually sand or crushed stone) with known properties, where as in the uncontrolled case, the installation is in native Finnish soil which is a highly organic and peaty soil having density of less than 960 kg/m^3. The thermal resistivity of these kinds of soils can be more than 5 K.m/W if the moisture contents are only 10-15 % [7]. Low moisture content also makes the environment more susceptible to moisture migration. The native soil in the worst case may be fully dried out due to a long-term dry period and the effect of vegetation. It has been observed that vegetation like trees are able to absorb practically all moisture in an area close to their roots. This observation should affect installation and maintenance procedures in cases where the cable is laid directly in the native soil. Table 1 gives a brief description of each of the above mentioned environmental conditions in terms of its ambient temperature, soil resistivity ρ_s, and dry soil resistivity ρ_{dry}.

Table 1. The various environmental parameters

Environmental condition	Ambient temperature (°C)	ρ_s (K.m/W)	ρ_{dry} (K.m/W)
a	20	1.2	-
b	20	1.2	2.5
c	20	1.2	5
d	20	5	-

Cable ampacity calculations

The cable ampacity calculations (tolerable load current determination for a given conductor temperature and vice versa) for different installations under various environmental conditions have been made using an algorithm based on analytical equations [6]. The algorithm is based on analytical methods developed in [6], which enable moisture migration modeling, even from tube installations. The tube modeling itself is largely based on methods developed by Neher and McGrath [1]. The algorithm is run in Mathcad®.

The calculations are performed for different cross-sections of the conductors used to carry different magnitudes of power or current magnitudes. The conductor data for different cross-sections is collected from the cable manufacturer's data sheet [8]. The allowable temperature limits are 65 °C and 90 °C as given in the data sheet. The nominal current rating for a given temperature is taken from the data sheet. The per unit (p.u.) current ratings are obtained by dividing the calculated current ratings by the nominal current ratings. The thermal capacities of the conductor are also calculated for the given current ratings in the data sheet. The following Tables illustrate the calculated ampacity data for different cable installations under various environmental conditions. Some values are replaced by a subscript UD (un-determined) where the calculated temperature is more than 1000 °C, showing an unrealistic situation.

In direct burial calculations, the effect of moisture migration can be clearly seen in terms of its lower current loadings at given temperatures or higher temperatures at given rated current loadings. However, in tube installation calculations, the effect of moisture migration is not dominant for controlled and uncontrolled environments as can be seen in the direct burial case (see Table 3 and Table 4).

Table 2. Ampacity calculations for direct burial without moisture migration and with moisture migration in controlled environment

Sr. No.	Cross sectional area (mm^2)	Direct burial without moisture migration (moist environment), ρ_s=1.2 K.m/W				Direct burial with moisture migration in controlled environment, ρ_s/ρ_{dry}=1.2/2.5 K.m/W			
		p.u. current rating		Conductor temperature at rated load (^oC)		p.u. current rating		Conductor temperature at rated load (^oC)	
		65^oC	90^oC	65^oC	90^oC	65^oC	90^oC	65^oC	90^oC
1	70	0.85	0.87	86	121	0.77	0.74	139	252
2	95	0.87	0.87	83	120	0.78	0.74	133	251
3	120	0.87	0.86	82	126	0.78	0.72	132	278
4	150	0.86	0.84	84	132	0.77	0.70	138	305
5	185	0.89	0.83	80	137	0.79	0.67	127	328
6	240	0.88	0.80	81	150	0.78	0.66	132	392
7	300	0.87	0.80	82	143	0.77	0.67	133	356

Table 3. Ampacity calculations for direct burial with moisture migration in uncontrolled environment and in fully dry environment

Sr. No.	Cross sectional area (mm^2)	Direct burial with moisture migration in uncontrolled environment, ρ_s/ρ_{dry}=1.2/5 K.m/W				Direct burial with moisture migration in fully dry environment, ρ_s=5 K.m/W			
		p.u. current rating		Conductor temperature at rated load (^oC)		p.u. current rating		Conductor temperature at rated load (^oC)	
		65^oC	90^oC	65^oC	90^oC	65^oC	90^oC	65^oC	90^oC
1	70	0.71	0.65	422	UD	0.46	0.47	642	UD
2	95	0.72	0.65	380	UD	0.46	0.47	584	UD
3	120	0.72	0.63	372	UD	0.47	0.46	572	UD
4	150	0.71	0.62	418	UD	0.46	0.44	633	UD
5	185	0.73	0.6	347	UD	0.47	0.44	536	UD
6	240	0.72	0.59	377	UD	0.46	0.42	560	UD
7	300	0.71	0.59	371	UD	0.46	0.42	563	UD

Table 4. Ampacity calculations for tube installation without moisture migration and with moisture migration in controlled environment

Sr. No.	Cross sectional area (mm^2)	Tube installation without moisture migration (moist environment), ρ_s=1.2 K.m/W				Tube installation with moisture migration in controlled environment, ρ_s/ρ_{dry}=1.2/2.5 K.m/W			
		p.u. current rating		Conductor temperature at rated load (^oC)		p.u. current rating		Conductor temperature at rated load (^oC)	
		65^oC	90^oC	65^oC	90^oC	65^oC	90^oC	65^oC	90^oC
1	70	0.74	0.77	109	155	0.75	0.73	140	236
2	95	0.76	0.77	105	154	0.76	0.72	135	240
3	120	0.76	0.76	104	163	0.76	0.70	135	267
4	150	0.75	0.74	107	170	0.75	0.69	141	288
5	185	0.77	0.73	102	177	0.77	0.68	131	314
6	240	0.76	0.70	103	195	0.76	0.65	136	379
7	300	0.76	0.71	104	187	0.75	0.66	140	371

Table 5. Ampacity calculations for tube installation with moisture migration in uncontrolled environment and in fully dry environment

Sr. No.	Cross sectional area (mm^2)	Tube installation with moisture migration in uncontrolled environment, ρ_s/ρ_{dry}=1.2/5 K.m/W				Tube installation with moisture migration in fully dry environment, ρ_s=5 K.m/W			
		p.u. current rating		Conductor temperature at rated load (^oC)		p.u. current rating		Conductor temperature at rated load (^oC)	
		65^oC	90^oC	65^oC	90^oC	65^oC	90^oC	65^oC	90^oC
1	70	0.75	0.67	251	773	0.49	0.5	390	UD
2	95	0.76	0.68	247	887	0.49	0.5	380	UD
3	120	0.76	0.66	244	UD	0.49	0.48	378	UD
4	150	0.75	0.65	270	UD	0.48	0.48	409	UD
5	185	0.76	0.63	248	UD	0.5	0.46	372	UD
6	240	0.74	0.60	284	UD	0.47	0.43	443	UD
7	300	0.74	0.60	283	UD	0.48	0.45	412	UD

Results and discussion

The results drawn for the direct burial and tube installations under various environmental conditions at different permissible temperatures using the calculated data given in the previous section are shown in Figs. 1 and 2, respectively. It is revealed from Fig. 1 that for the same temperature rise in direct burial, the current rating of the conductor tends to decrease as the moisture contents decrease. In other words, a conductor operating at the rated loading must have a higher temperature than the permissible limit given by the manufacturer. It can be concluded from Fig. 2 that for the same temperature rise in tube installation, the current rating of the conductor tends to decrease (from the rated loading given by the manufacturer) as the moisture contents decrease. In other words, a conductor operating at the rated loading must have a higher temperature than the permissible limit. It is also clear that moisture contents do not have a significant effect on the conductor current rating in case of tube installation (specifically for a 65°C permissible temperature limit), however, a significant effect can be seen for the fully dry environment (worst case) at different permissible temperatures.

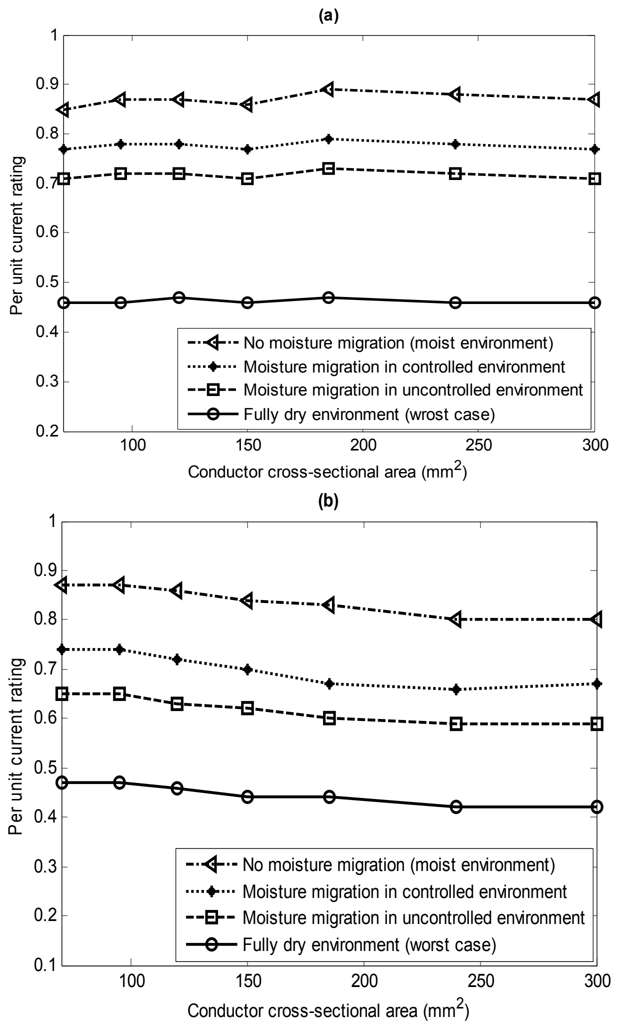

Fig. 1. P.u. current ratings for direct burial under various environmental conditions for different cross-sections of conductor at (a) 65 °C (b) 90 °C

The p.u. current ratings for direct burial and tube installation are compared at different temperatures for various installation environment conditions and are given in Fig. 3 at 65°C temperature. It is clear from Fig. 3 that in cases (a) and (b), the direct burial has higher current ratings; however, in cases (c) and (d), the tube installation has higher current ratings. Therefore, it is suggested that tube installation should be preferred in the case of a typical Finnish uncontrolled environment. Similar results are observed at the permissible temperature limit of 90°C as shown in Fig. 4. The p.u. current ratings for direct burial and tube installation are compared at different permissible temperatures for various installation environmental conditions at minimum and maximum conductor cross-sections. This analysis will be helpful to investigate the effect of conductor diameter on the calculation methodology. In the data sheet, the conductor has minimum and maximum cross-sectional areas of 70 and 240 mm^2, respectively.

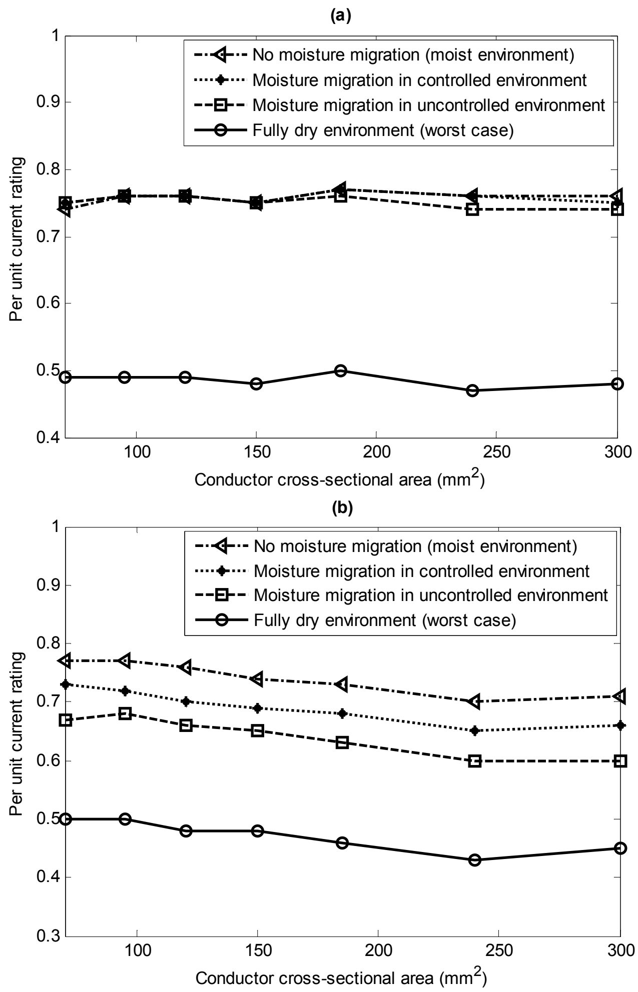

Fig. 2. P.u. current ratings for tube installation under various environmental conditions for different cross-sections of conductor at (a) 65°C (b) 90°C

A comparative study for direct burial and tube installation has been carried out for minimum and maximum cross section areas at a permissible temperature of 65 °C as shown in Figs. 5 and 6, respectively.

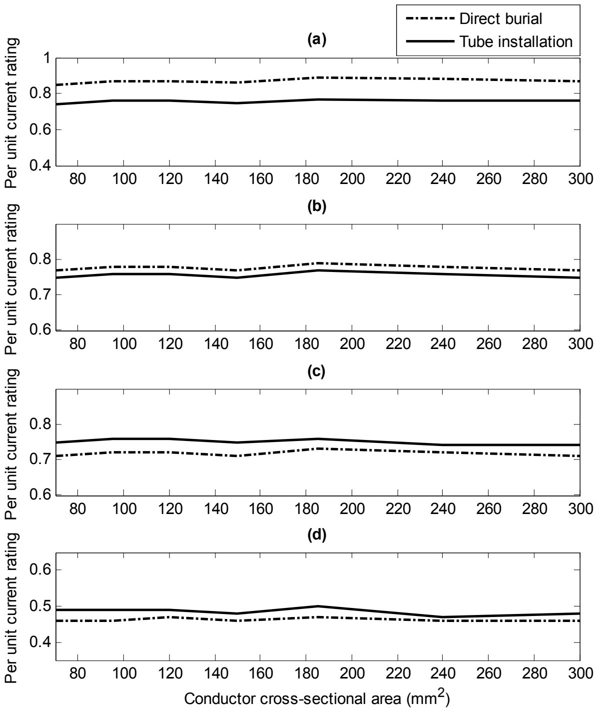

Fig. 3. Direct burial versus tube installation for conductor at 65°C temperature in (a) no moisture, (b) moisture migration in controlled environment, (c) moisture migration in uncontrolled environment, (d) fully dry environment

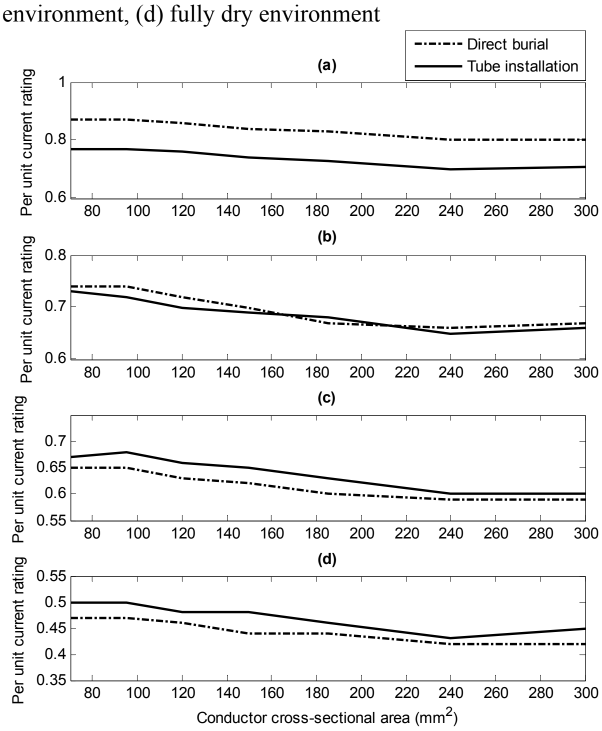

Fig. 4. Direct burial versus tube installation for conductor at 90°C temperature in (a) no moisture, (b) moisture migration in controlled environment, (c) moisture migration in uncontrolled environment, (d) fully dry environment

It is revealed from Fig. 5 that under the permissible limits of temperature rise, the conductor current rating is higher in the case of direct burial installation for the first two environmental conditions (a and b). However, the conductor current rating is higher in the case of tube installation for the other two environmental cases (c and d). It can be concluded that the current rating pattern does not change under the different environmental conditions for minimum or maximum conductor cross-sectional area (Fig. 5 and Fig. 6), which proves the applicability of this technique to determine current rating for any size of conductor.

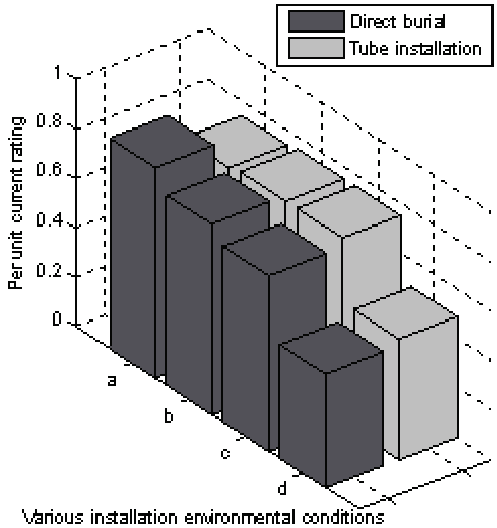

Fig. 5. Direct burial versus tube installation for conductor at 65°C temperature having maximum cross- sectional area of 70 mm^2 under various installation environmental conditions

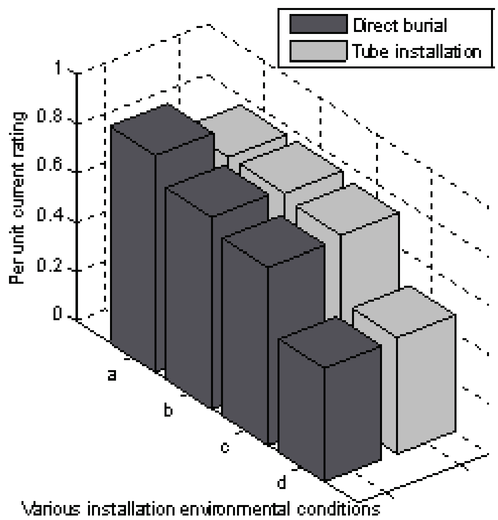

Fig. 6. Direct burial versus tube installation for conductor at 65°C temperature having maximum cross- sectional area of 240 mm^2 under various installation environmental conditions

Conclusions

An analytical formulation for the calculation of current loading for 3-phase MV power cables under various environmental conditions has been presented. As the moisture content decreases due to the moisture migration phenomenon occurring in the vicinity of a cable, the current rating of the conductor also decreases for the same permissible thermal limits. Therefore, it is suggested to load the cables at lower current ratings than those given in the specifications for safe and reliable operation.

In case of direct burial or tube installation, the current rating decreases (from the rated loading given by the manufacturer) due to moisture migration. However, the effect is more significant in the case of direct burial. Slightly higher current ratings are obtained in the case of tube installation for a typical Finnish uncontrolled environment (but note, these ratings are substantially lower than the catalogue values!).

The pattern of decreasing current rating due to moisture migration under various environmental conditions is the same for minimum or maximum conductor cross-sectional area, which proves the applicability of this technique for any size of conductor.

In the worst case, fully dried out peaty native soil, the load capacity of the cables is reduced to less than 50% of the normal rating. This scenario is possible during a long-term dry period, especially if there is vegetation close to the cable route.

The investigation carried out in this paper will be useful for electric power utilities to revise allowable current ratings to avoid damage to their power cables as well as for the safe and reliable distribution of power to their customers. In this way, the new distribution power cable installations can be partially delayed and better asset management can be carried out in the challenging future smart grid environment.

References

1. **Neher J. H., McGrath M. H.** The calculation of the temperature rise and load capability of cable systems // AIEE Trans., 1957. – Vol. 76. – P. 752–772.
2. **IEC Publication 60287–3–1**. Calculation of the Continuous Current Ratings of Cables. – 1982. – 35 p.
3. **Anders G. J.** Rating of Electric Power Cables. – McGraw Hill. New York. 1997. – 427 p.
4. **Hwang C. C., Chang J. J., Chen H. Y.** Calculation of ampacities for cables in trays using finite elements // Electric Power Systems Research, 2000. – Vol. 54. – P. 75–81.
5. **Chaban M., Leduc J**. Using the finite element method for complex cable ampacity calculations: A more accurate and much more flexible alternative to the conventional analytical methods // Proc. of the 5th Int. Conf. on Insulated Power Cables. – Paris, France, 1999. – P. 20–24.
6. **Millar R. J**. A Compressive Approach to Real Time Power Cable Temperature Prediction and Rating in Thermally Unstable Environments, PhD dissertation. – Helsinki University of Technology (TKK), Finland, 2006.
7. **Boggs S. A., Chu F. Y., Radhakrishna H. S., Steinmanis J. E.** Underground Cable Thermal Backfill // Proceedings of the Symposium on Underground Cable Thermal Backfill. – Toronto, 1982.
8. **Hyvönen P.** Prediction of Insulation Degradation of Distribution Power Cables Based on Chemical Analysis and Electrical Measurements, Doctoral Dissertation. –Espoo, Finland, 2008.
9. **Millar R J., Lehtonen M.** Cable Ampacity – A Finnish Perspective // Power Systems and High Voltage Engineering. – Helsinki University of Technology (TKK), Publication series, TKK–SVSJ–1, 2006.

Received 2011 06 20
Accepted after revision 2011 09 20

M. Hashmi, R. J. Millar, M. Lehtonen, S. Hanninen. Effect of Climate Change on MV Underground Network Operations in the Future Smart Grid Environment // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 9(115). – P. 27–32.

In this paper, the steady state current rating calculations for 3-phase XLPE distribution power cables are performed using an analytical set of thermal equations. The analysis is made for different installation configurations (direct burial and tube installations) under various possible extreme Finnish environmental conditions. This study will enable electric power utilities to revise allowable current ratings to avoid damage to their power cables as well ensure safe and reliable distribution of power to the customers in the future smart grid environment. Ill. 6, bibl. 9, tabl. 5 (in English; abstracts in English and Lithuanian).

M. Hashmi, R. J. Millar, M. Lehtonen, S. Hanninen. Klimato kaitos poveikis vidutinės įtampos kabelinio tinklo darbo sąlygoms ateities sumaniajame tinkle // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 9(115). – P. 27–32.

Šiame straipsnyje pateikti nusistovėjusio režimo srovių vertės trifaziuose XPLE tipo elektros energijos paskirstymo kabeliuose analitinių skaičiavimų rezultatai, gauti įvertinant šiluminių procesų įtaką. Skaičiavimai atlikti esant skirtingiems kabelių klojimo būdams (grunte, vamzdžiuose), įvertinant įvairias galimas ribines Suomijos aplinkos sąlygas. Naudodamosi šia studija, elektros tinklų įmonės gali peržiūrėti leistinus srovių dydžius, kad išvengtų kabelinių linijų pažeidimų ir užtikrintų saugų ir patikimą elektros energijos tiekimą vartotojams ateities sumaniuosiuose tinkluose. Il. 6, bibl. 9, lent. 5 (anglų kalba; santraukos anglų ir lietuvių k.).