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Thermal Analysis of Underground Distribution Cables under Dynamic Loading in the Presence of Harmonic Load Currents

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***Abstract*—As it is known that the increasing of harmonic currents levels on distribution system have effected on the cable current capacity. Harmonic current orders will cause increasing in the temperature of the conductor inside the cable which may exceed the limit value. The goal of this paper is to study thermal analysis of distribution cables to calculate the temperature distribution inside the cable layers and its surrounding soil in the presence of harmonic current order under daily load current cycle, taking into account the phenomena of a dry zone formation. Consequently, a de-rating factor is calculated in this study due to the harmonic currents effects. The thermal model of the cable is considered according to IEC 60853-2 standard, including the effects of current harmonics on temperature of the cable parts and its surrounding soil. Additionally, the finite element method is used to obtain temperature maps of the cable and the around soil. Calculations showed that the time of dry band creation is decreased when the level of harmonic increases in the loading current cycle. This study is done on the distribution system cables have voltage level 0.4 kV and 22 kV.**

Keywords — Distribution cable, thermal analysis, lumped model, harmonic currents, de-rating factor, dry band.

I. INTRODUCTION

The current carrying capacity (ampacity) of underground distribution cables are based on the properties of the cable constrictions and the physical characteristics of surrounding soil according to the standard specification IEC 60287-1-3 [1]. Due to the increase uses of nonlinear loads in all needs and in all application. It is resulted in gradually high level of harmonic currents [2, 3]. Under variable loads, the cable losses generate heat. This heat leads to decrease the humidity content of the around soil. Also, dry zone may be formed surrounding the cable. So, thermal soil resistance increasing and interruption the heat dissipation from the soil around the cable [4-8]. Thermal performance of the underground cables using two-dimensional finite element method is described in [9-13]. In the above mentioned references, the computations of thermal analysis and ampacity in the presence of harmonic current orders is missed. Many studies have discussed the effects of harmonic current on the increasing temperature of the cables in [14-18]. The effects of harmonic current on the underground cable are performed considering harmonic measurements in [19]. A dynamic de-rating factor of the power cables as a result of current harmonic distortion through a dynamic thermal modeling of three-phase underground cable is performed in [20]. The power losses in the cables are analyzed, including both sinusoidal waveform and different harmonic currents are performed in [21]. Dynamic thermal analysis is done for calculation of cable layers temperature as well as de-rating factor in different harmonic signatures based on IEC standard in [22]. The harmonic current loading profiles used in this study are taken from IEEE scenarios [2, 23]. In this paper, different harmonic current profiles are considered so as to study the effect of harmonic profiles on the temperature distribution inside the different parts of the cable and the around soil taking into consideration soil resistivity variation during daily load cycle. Moreover, a de-rating factor of the cable loading should be included in the calculation process. At first the calculations are done on thermal model of the cable by applying sinusoidal current waveform. Thereafter, the computation of cable parts and its surrounding soil temperatures are done by applying the effect of current harmonics order on load cyclic current at constant and variation of thermal soil resistivity. The calculations are done by using MATLAB and COMSOL multiphysics programs. For this study using single core 22 kV cable arranged in flat formation and three core 0.4 kV cable.

II. THERMAL MODELING OF UNDERGROUND DISTRIBUTION CABLES

A. *Without Harmonic Distortion Effect on the Distribution Cable Losses*

The cable parts are performed by lumped model thermoelectric equivalent method (TEE) according to IEC 60853-2 [24]. Thermal models of distribution cable is done to study the dynamic temperature inside the different parts of the underground distribution cable and the around soil as shown in Fig. 1. In this figure the thermal resistances of the metallic layers and the passing current in an analogue electric circuit of the distribution cable are ignored.

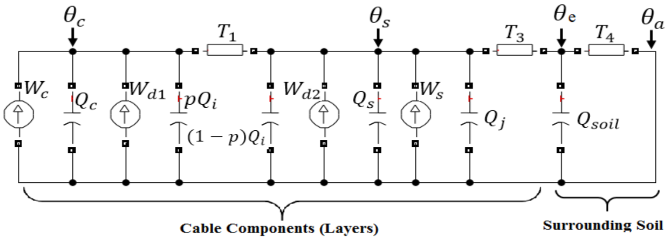

Fig. 1. Thermal equivalent circuit of single core cable parts and the around soil.

Consequently, the current sources in the thermal model represent the heat sources in the metallic parts inside the cable. The cable losses of the conductor (W_c) are produced by the resistance of the conductor.

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Screen losses (W_s) are because of circulating current flowing in the cable sheath. The insulation losses (W_{d1}) and (W_{d2}) are dependent on the insulation material type and ignored for low voltage cables. The θ_c , θ_e and θ_s are conductor, jacket and screen temperature above the surrounding temperature (θ_a), respectively. Therefore, p is van wormer coefficient. The losses of single core distribution cable layers are calculated as follow [1]:

$$W_c = I^2 . R_{ac} \tag{1}$$

$$W_s = W_c . \lambda_1 \tag{2}$$

Where, I, R_{ac} and λ_1 are load current, conductor electrical resistance and sheath loss factor, respectively. The thermal capacitances and resistances of the cable in each part and the around soil are calculated as given in [1, 24].

$$Q_c = C_{pc} . A_c \tag{3}$$

$$Q_i = \frac{\pi}{4}(D_i^2 - d_c^2)C_{pi} \tag{4}$$

$$Q_s = \frac{\pi}{4}(D_s^2 - D_i^2)C_{ps} \tag{5}$$

$$Q_j = \frac{\pi}{4}(D_e^2 - D_s^2)C_{pj} \tag{6}$$

$$Q_{soil} = \pi\left(L^2 - \left(\frac{D_e}{2}\right)^2\right)C_{psoil} \tag{7}$$

$$T_1 = \frac{\rho_i}{2\pi}\ln\left(\frac{D_i}{d_c}\right) \tag{8}$$

$$T_3 = \frac{\rho_j}{2\pi}\ln\left(\frac{D_e}{D_s}\right) \tag{9}$$

$$T_4 = \frac{\rho_{soil}}{2\pi}\left\{\ln\left(\frac{4L}{D_e}\right) + \ln\left(1 + \left(\frac{2L}{S}\right)^2\right)\right\} \tag{10}$$

Where, Q_c, Q_s, Q_i, Q_j and Q_{soil} are the conductor, screen ,insulation, jacket and surrounding soil thermal capacitance, respectively. d_c, D_s, D_i and D_e are the conductor, screen ,insulation and the cable surface external diameter, respectively. T_1, T_3 and T_4 are thermal resistance of the insulation, jacket and surrounding soil, respectively. ρ_{soil}, ρ_j and ρ_i are the thermal resistivity of surrounding soil, jacket and insulation, respectively. C_{pc}, C_{ps}, C_{pi}, C_{pj} and C_{psoil} are volumetric specific heat of the cable layers material and the soil around it. L, A_c and S are burial depth, area of the conductor and the distance between the cables in case of flat formation, respectively.

B. With Harmonic Distortion Effect on the Distribution Cable Losses

In this article, single core cable in flat formation and three core cable are loaded with and without harmonic current effect. The fundamental frequency and harmonic order frequencies are considered in transient harmonic analysis. Taking into account harmonic current at each frequency and total harmonic distortion current losses are estimated. Odd-orders harmonic current are determined. The conductor resistance in (Ω/m) without harmonic effects according to IEC-60287-1 [1].

$$R_{ac} = R_{dc}(1 + Y_s + Y_p) \tag{11}$$

Where R_{dc} is the cable conductor DC resistance at the permissible operating temperature defined in IEC-60287-1 [1]. Y_p and Y_s are the proximity and skin effect factor can be used to calculate the effects of harmonic current orders on the increasing of temperature in distribution cable layers. Due to increasing the harmonic current orders will cause increase in the R_{ac} as consequence dependent on proximity and skin factor. These factors dependent on frequency change as follow [1]:

$$Y_s = \frac{{x_s}^4}{192 + 0.8\,{x_s}^4} \tag{12}$$

$$Y_p = \left[\frac{{x_p}^4}{192 + 0.8{x_p}^4}\right].\left(\frac{d_c}{S}\right)^2.\left[0.312.\left(\frac{d_c}{S}\right)^2 + \left(\frac{1.18}{\frac{{x_p}^4}{192 + 0.8{x_p}^4} + 0.27}\right)\right] \tag{13}$$

Where x_s and x_p equations are given in IEC 60287-1. Consequently, for a non-sinusoidal current as a result of harmonic orders, the I_{rms} is root mean square current can be defined in relation of harmonic order (*h)* as given in (14). The losses in distribution cables are depended not only on the total harmonic distortion (THD), but also on the magnitude of each harmonic orders. IEEE Standard 519 recommended limitation on both them in [2].The THD is used to express the effect of harmonic currents on the distribution cable, it is a percentage as shown in (15).

$$I_{rms} = \sqrt{{I_1}^2 + \sum_{h=2}^{\infty}{I_h}^2} = I_1\sqrt{1 + (THD)^2} \tag{14}$$

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty}{I_h}^2}}{I_1} \tag{15}$$

In case of odd harmonics current orders, the conductor power losses W_{c1} can be calculated at each frequency and summed by:

$$W_{c1} = (I_1)^2.\left(R_{ac(1)} + \sum_{h=3}^{\infty}{H_h}^2.R_{ac(h)}\right) \tag{16}$$

Where $I_1$and $R_{ac(1)}$ are the current component and AC conductor resistance at fundamental frequency in case of non-sinusoidal waveform, respectively. H_h is the percentage harmonic load current and $R_{ac(h)}$ is the conductor resistance of harmonic frequency. A de-rating factor (K_d) is calculated when the R_{ac} / R_{dc} value and the harmonic orders of the current are given. It can be expressed as indicated in (17) [17].

$$K_d = \sqrt{\frac{1}{1 + \sum_{h=3}^{\infty}({I^2}_h(pu)\frac{R_{ac(h)}}{R_{dc}})}} \tag{17}$$

Where $0 < K_d \leq 1$ and ${I^2}_h(pu)$ is value of pu current. In this article, the current harmonics distortion for distribution cables system is taken account and all the odd-orders harmonic up to order 49th are studied. All the higher orders, even and zero harmonic orders are neglected. On the other side, the relations of the thermal soil resistivity with humidity content of the soil and the soil temperature are included in this study. The common equation of thermal soil resistivity (ρ_{soil}) as given in (18) [25].

$$\log_{10}\rho_{soil} = (g_1 - g_2\gamma_d)x_1(\theta_{soil}) + \frac{g_3}{g_4 + \frac{G_1}{x_2(\theta_{soil})}} \tag{18}$$

Where, G_1, θ_{soil} and γ_d are the humidity content, temperature and dry density of the soil, respectively. The variables x_1 and x_2 are defined in [25]. Also, the constant value $g_1$to g_7 can be find in [25].

III. SIMULATION RESULTS OF THERMAL MODEL

The construction parts of 22 and 0.4 kV distribution cables are presented in Fig. 2. The transient load current cycle for 22 and 0.4 kV cables for 72 hours are given in Fig. 3. The conductor type, cross section area and load current cycle of each cable are taken from Egyptian national electrical grid company reports [26]. The thermal analysis are presented taking into account the variation of soil resistivity and the effect of harmonic current. The study is done on 22 kV single-core cable and 0.4 kV three-core cable.

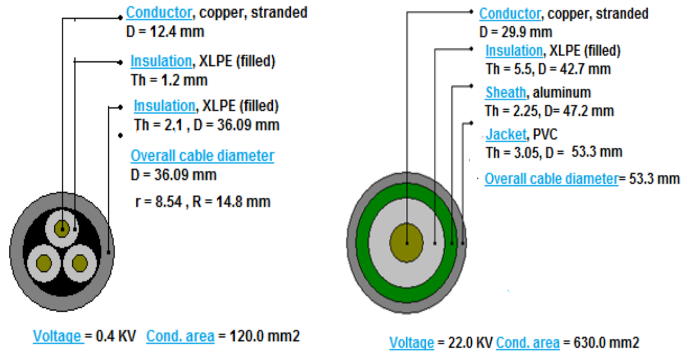


Fig. 2. Construction parts of 0.4 kV and 22 kV cables.

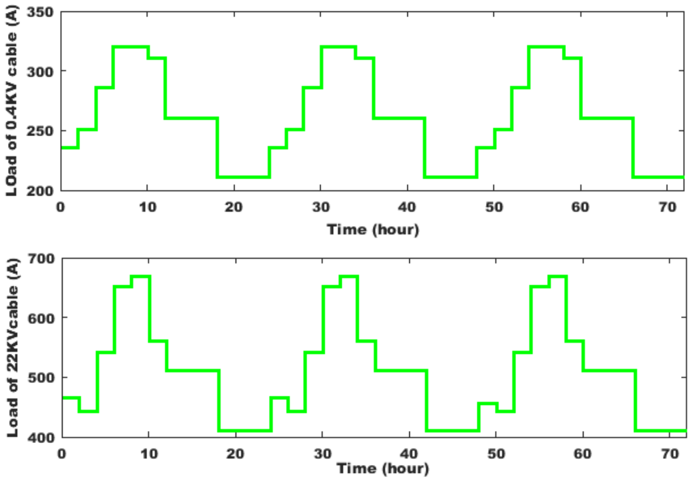


Fig. 3. Load current cycles of cables under study.

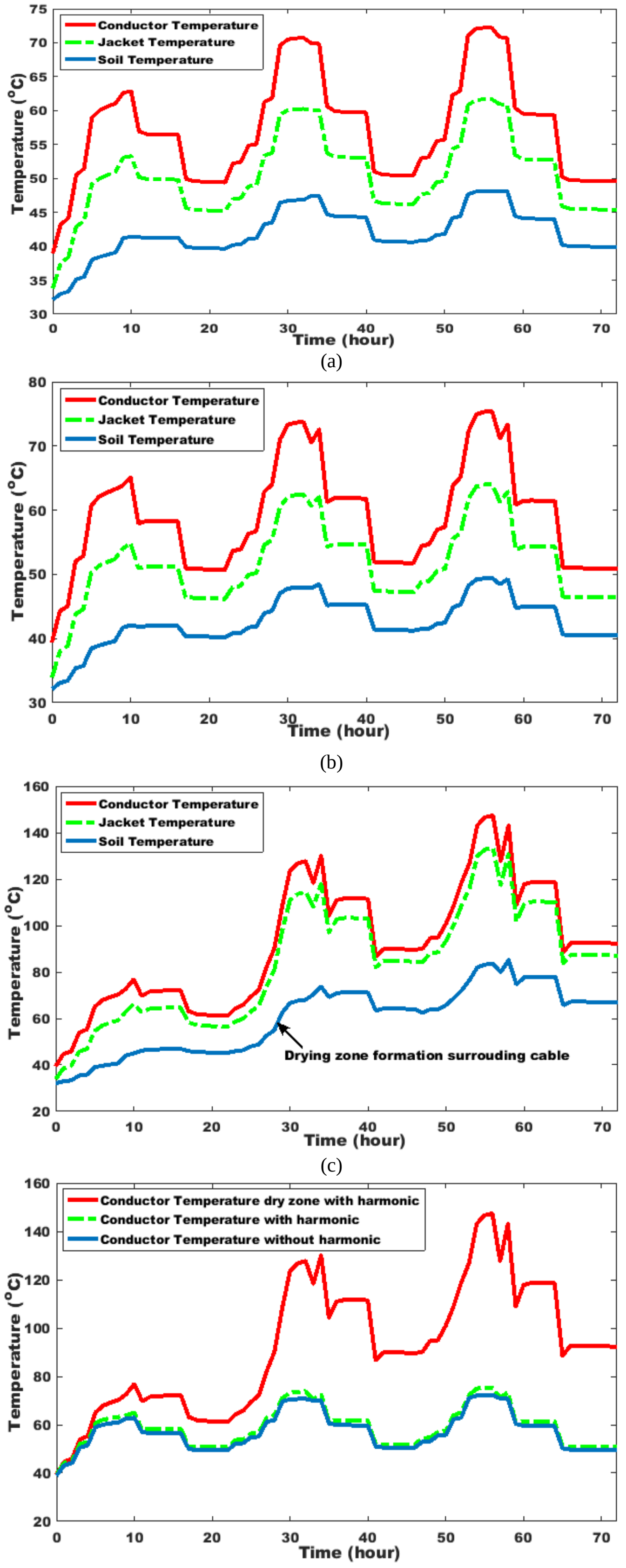
A. *0.4 KV Cable Thermal Analysis*

The simulation results obtained are includes the effect of harmonic current on the temperature of cable parts and the soil around it. Harmonic current profiles as shown in Table I are taken from IEEE scenarios [2, 23]. Profile A is for 12-pulse converter add to cycling load current. Profile C is the unfiltered and most filtered harmonic distortion. The IEC 60853-2 method is used in the program calculations. The construction of the used soil are mixture 85% sand, 15% clay and 0.03 humidity content of the soil (m^3/m^3). Its wet thermal resistivity 0.968 ($^oC.m/W$) and dry density 1588 (Kg/m^3) [4]. A study is carried out for 0.4 kV three-core cable and its laying depth is 0.6 m. So, the dynamic temperature of the cable layers and its surrounding soil are calculated by using the lumped parameter model. Fig. 4(a) shows the transient temperature of the cable elements and its surrounding soil. The cable is considered at constant thermal resistivity and applying the daily load current as shown in Fig. 3. It is observed that the maximum temperature of the conductor cable is approximately 72.5 °C. It is observed also that if the harmonic current profile A with total harmonic distortion spectrum (THD= 25.7%) is added as percentage of fundamental current load cycle, this effect on temperature of distribution cable. The obtained results at constant resistivity are shown in Fig. 4(b). In this figure the temperature of the conductor increases to 77 ^{o}C and noticed also the soil temperature increases to 48 ^{o}C due to the presence of harmonic orders.

The dynamic temperature of the cable layers at thermal resistivity of the soil variation with temperature of the soil and harmonic current profile A is added to load current cause increasing in the cable parts temperature and its surrounding soil as shown in Fig. 4(c). In this figure the temperature of the conductor cable reaches to 150°C instead of 77°C in Fig. 4(b). It is noticed also the dry zone formation around the cable appear after 28 hours of starting loading by harmonic current of the cable. According to [4] the soil dry zone is appear at 60°C. An instantaneous de-rating factor (K_d = 0.9286) at time 28 hours. Fig. 4(d) shows the comparison between conductor temperatures in above three states. The results are obtained by applying profile A to the load current cyclic and thermal resistivity of the soil variation with time. The temperature of the conductor cable increase by $\sim 106\ \%$ as compared with its value in the sinusoidal current waveform at fundamental frequency (50 Hz). One interesting observation is that the presence of harmonic current and thermal resistivity of the soil variation with time have significant impact in the temperature of the conductor and the around soil. The thermal analysis of the cable parts and its surrounding soil are obtained using (COMSOL) multiphysics program. This program is used to show the temperature degrees in different parts of study cable and its surrounding soil. Fig. 5 illustrates temperature maps of three core 0.4 kV cable parts when the cable is loaded with harmonic current profile A as percentage of fundamental current load cycle. The temperature of the conductor cable reaches to 72.7°C. Similar results have been obtained by the COMSOL program. It is almost equivalent to the results obtained by thermal calculation analysis with about 3°C difference between them at constant thermal soil resistivity.

TABLE I. HARMONIC PROFILE BASED ON PERCENTAGE OF FUNDAMENTAL [2, 23]

Harmonic order	**Scenario**		**Harmonic order**	**Scenario**	
	A	***C***		***A***	***C***
3rd	0	0	29th	1.4	0.7
5th	19.2	9.59	31st	1.2	0.6
7th	13.2	6.6	35th	1.1	0.55
11th	7.3	3.66	37th	1	0
13th	5.7	2.85	41st	0.9	0
17th	3.5	1.75	43rd	0.8	0
19th	2.7	1.35	47th	0.8	0
23rd	2	1	49th	0.7	0
25th	1.6	0.8	THD, %	25.7	12.8



(a)

(b)

(c)

(d)

Fig. 4. Temperature of 0.4 kV cable parts using lumped method (a) With sinusoidal current at constant resistivity, (b) With harmonic current profile A at constant resistivity, (c) With harmonic current profile A with changing thermal soil resistivity, (d) Comparison of temperature of the conductor cable in three stats.

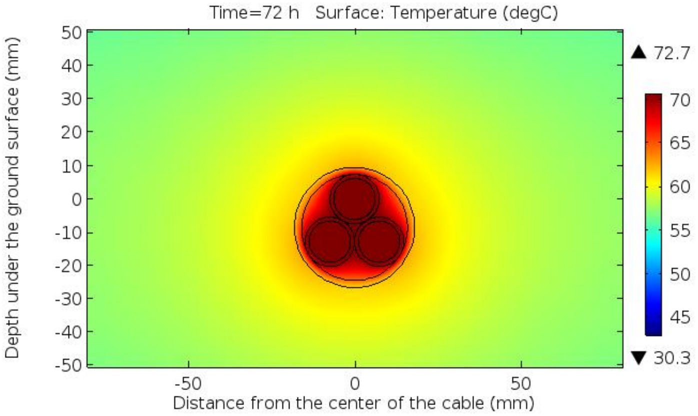


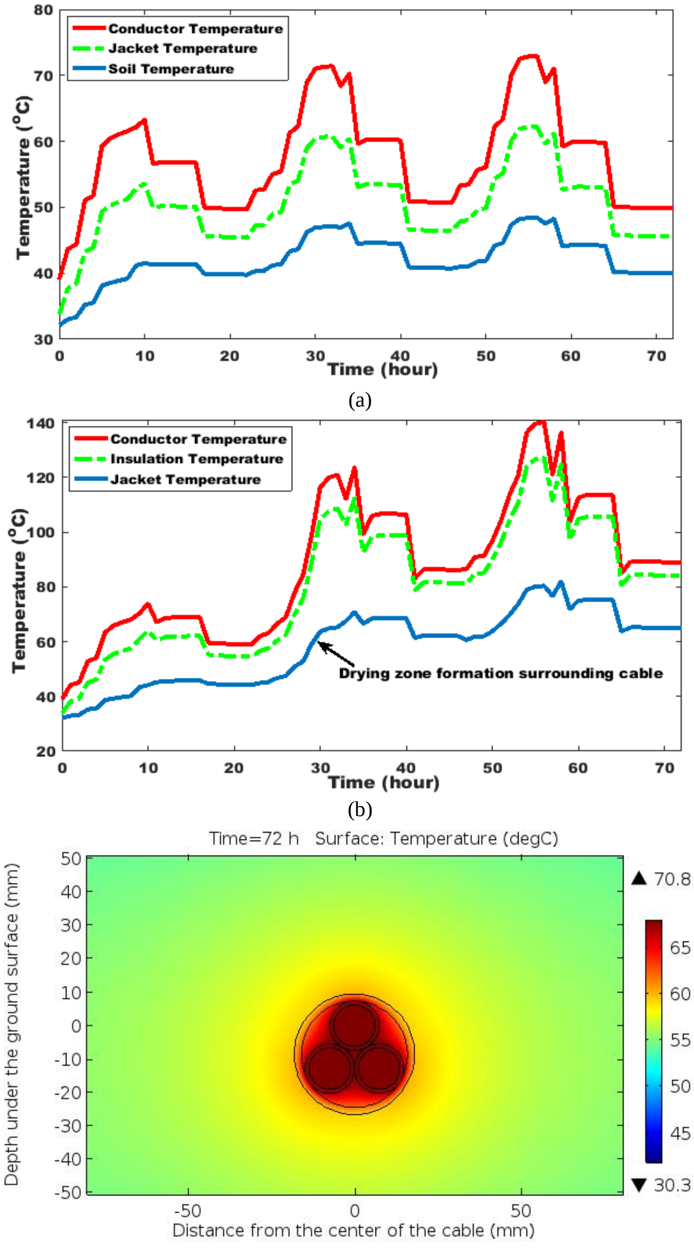
Fig. 5. COMSOL simulations of cable parts and its surrounding soil of 0.4 kV with harmonic current profile A at constant thermal resistivity of the soil.

It is observed also when added profile C with total harmonic distortion spectrum (THD= 12.8 %) to daily load current. Fig. 6(a) gives dynamic temperature of the cable, the maximum temperature of the conductor cable is approximately 74 °C at the constant thermal soil resistivity. While the thermal resistivity of the soil variation with time and harmonic current profile C is added to loading current. The temperature of the conductor reaches to about 141°C instead of 74°C and dry zone formation around the cable after 29 hours of starting loading by harmonic current as shown in Fig. 6(b). Also, an instantaneous de-rating factor (K_d = 0.9822). The results are obtained by applying profile C on daily load current and thermal resistivity of the soil variation with time in Fig. 6(b). It is observed that the temperature of the conductor cable increases by ~ 94.4 % as compared with its value in sinusoidal current waveform at fundamental frequency (50 Hz). Fig. 6(c) shows the heat map of cable components when the cable is load with harmonic profile C as percentage of fundamental current load cycle using the COMSOL program the temperature of the conductor cable reaches to 70.8°C.

B. 22 KV Cable Thermal Analysis

The similar study is carried out for single-core 22 kV cable is placed at 0.8 m buried depth with 0.106 m spacing between each cable and arranged in flat formation according to IEC 60287-1-3 [1]. The construction parts of 22 kV cable are shown in Fig. 2 and Fig. 3 gives the current load cycle. While the soil type used is similar to the soil type used around the 0.4 kV cable with 0.968(°C .m/W) constant thermal soil resistivity. The transient temperature of the cable elements and its surrounding soil at constant thermal soil resistivity is shown in Fig. 7(a). In this figure the maximum temperature of the conductor cable is approximately 58°C at sinusoidal current waveform with fundamental frequency (50 Hz). When current waveform is a non-sinusoidal due to harmonic disturbance percentage of highly harmonic distortion level of (THD= 50.11%) [20] and added to the current load cycle. The temperature of the conductor cable is effected as shown in Fig. 7(b). In this figure the temperature of the conductor increases to 63 °C and small increases in its surrounding soil temperature at constant thermal resistivity of the soil. In this part, the thermal resistivity of the soil variation with time and a highly harmonic distortion level of THD= 50.11% is added to fundamental current load cycle. The loading harmonic current increases the temperature of the conductor cable as shown in Fig. 7(c).

In this figure is observed that the temperature of the conductor increases to 96°C instead of 63°C in Fig. 7(b). It is noticed also dry zone formation around the cable after 53 hours of starting loading the cable by its dynamic loading with harmonic current as shown in Fig. 7(c). Also, an instantaneous de-rating factor (K_d = 0.7851). Fig. 7(d) shows the comparison between conductor temperatures in above three state. The results are obtained by applying highly percentage harmonic current distortion on daily load current and variation thermal soil resistivity with time, cause increasing in the temperature of the conductor to ~ 65.5 % as compared with its value in sinusoidal current waveform at fundamental frequency (50 Hz). Additionally, de-rating factors affected by an increase the presence of harmonic order in cyclic loading.

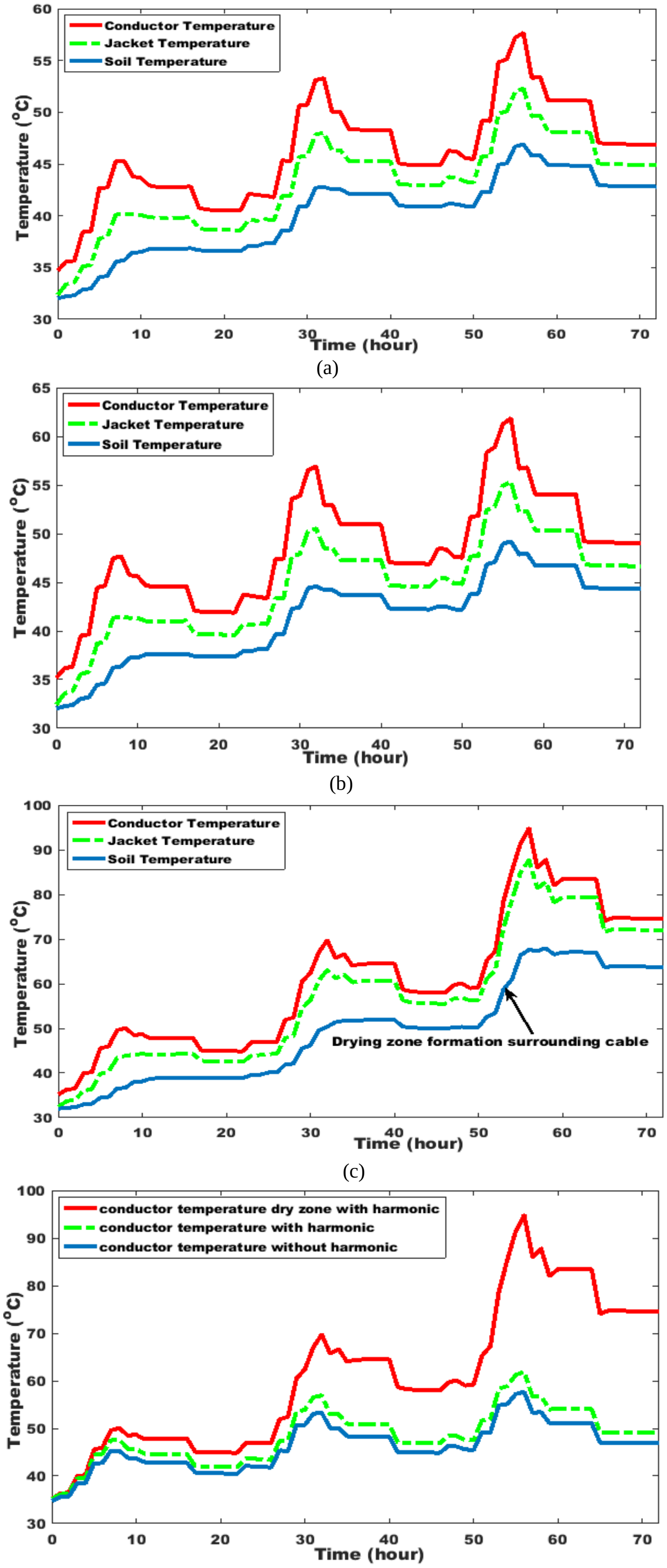


(a)

(b)

(c)

Fig. 6. Temperature of 0.4 kV cable parts using lumped method (a) With harmonic current profile C at constant resistivity, (b) With harmonic current profile C with changing resistivity, (c) COMSOL simulations of the cable and its surrounding soil with harmonic current profile C at constant resistivity.



(a)

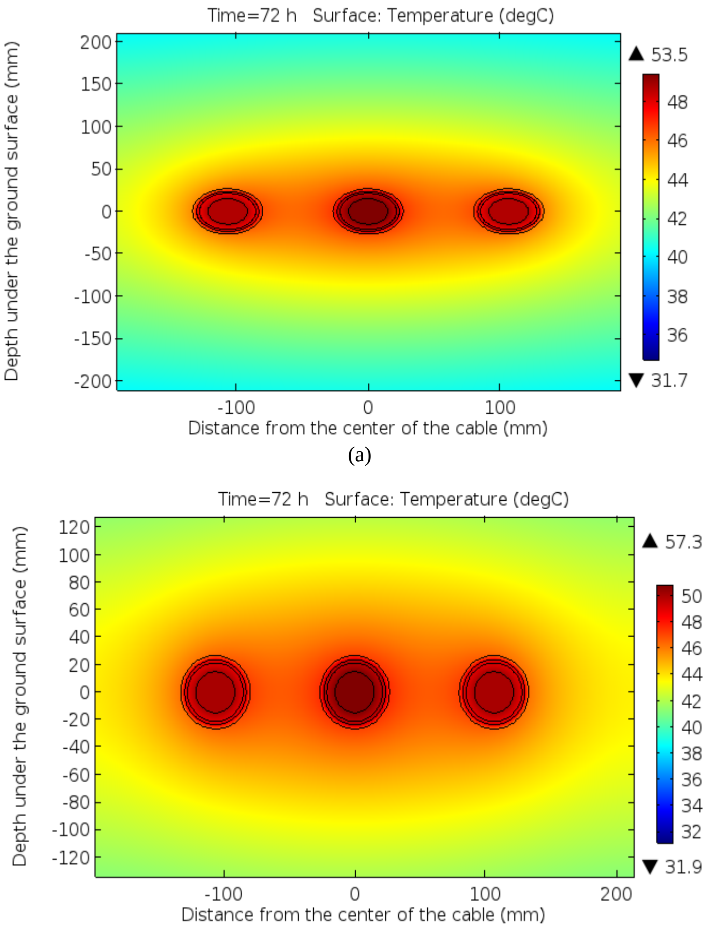
(b)

(c)

(d)

Fig. 7. Temperature of 22 kV cable parts using lumped method (a) With sinusoidal current at constant resistivity, (b) With a highly harmonic distortion level of THD= 50.11% at constant resistivity, (c) With a highly harmonic distortion level of THD= 50.11% with changing resistivity,(d) Comparison of temperature of the conductor cable between three stats.

The thermal analysis calculations of the cable parts and its surrounding soil is solved by using COMSOL multiphysics program. Fig. 8(a) gives the temperature map of the cable parts and the around soil of distribution power cable at a constant thermal soil resistivity of 0.968 (°C m/W), after 72 hours of daily loading cycle given in Fig. 2. It is show the conductor temperature reaches to 53.5 °C. Fig. 8(b) gives thermal analysis of cable under applying highly percentage harmonic current distortion on daily load current. It is showed harmonic current effects on the temperature of the conductor cable reaches to 57.3 °C at the same soil characteristic.



(a)

(b)

Fig. 8. COMSOL simulations of cable parts and its surrounding soil of 22 kV (a) With sinusoidal current at constant resistivity, (b) With a highly harmonic distortion level of THD= 50.11% at constant thermal soil resistivity.

Finally the paper results obtained from the study of harmonic profiles during daily load cycle of the distribution cables are shown in Table II. After the calculations are performed a note worthy of attention that harmonic current orders are added to cyclic load current which produce percentage THD. As shown in (14) percentage THD change in root mean squre load current cycle value. So, the temperature of the conductor cable and the around soil are increasing. Also, the percentage of THD affect on the time require to formation dry zone and increase the de-rating factor of the distribution cables.

TABLE II. SUMMARY OF HARMONIC CURRENT PROFILES DURING LOAD CYCLES OF DISTRIBUTION CABLES

0.4 kV Profile A	Temperature of the conductor (ºC)	THD %	25.7
		Without dry zone	77
		With dry zone	150
	Soil temperature (ºC)	Without dry zone	49
		With dry zone	85
	De-rating factor (K_d)	At starting of dry zone	0.9286
	Temperature of the conductor (ºC) using COMSOL		72.7
	Time to form dry zone (hour)		28
0.4 kV Profile C	Temperature of the conductor (ºC)	THD %	12.8
		Without dry zone	74
		With dry zone	141
	Soil temperature (ºC)	Without dry zone	47
		With dry zone	80
	De-rating factor (K_d)	At starting of dry zone	0.9822
	Temperature of the conductor (ºC) using COMSOL		70.8
	Time to form dry zone (hour)		29
22 kV Highly distortion level	Temperature of the conductor (ºC)	THD %	50.11
		Without dry zone	63
		With dry zone	96
	Soil temperature (ºC)	Without dry zone	48
		With dry zone	65
	De-rating factor (K_d)	At starting of dry zone	0.7851
	Temperature of the conductor (ºC) using COMSOL		57.3
	Time to form dry zone (hour)		53

IV. CONCLUSIONS

In this article, thermal analysis calculations of distribution cables parts and its surrounding soil under sinusoidal current and harmonic current profiles are performed. The current harmonics cause increasing in the temperature of the conductor cable and the around soil. Due to the harmonic current orders, the R_{ac} is increasing. Consequently, power losses are increasing due to the increasing value of R_{ac} as given in (16). The IEC 60853-2 thermal model is used to calculate the temperature of the cable parts and the around soil. It is observed that in case of 0.4 kV cable the temperature of the conductor increases by ~ 77.5 °C as compared with its value in the sinusoidal current by applying profile A to load current and thermal resistivity of the soil variation with time. But, by applying profile C the temperature of the conductor increases by ~ 68.5 °C as compared with its value in sinusoidal current. It is noticed that extremely increase in the cable parts temperature and dry zone formation time around the cable is different. In case of 22 kV cable the temperature of the conductor increases by~ 38°C as compared with its value in the sinusoidal current by applying highly harmonic distortion level. The temperature maps of the cable parts and the around soil are obtained by (COMSOL) multiphysics program in each case of sinusoidal and non-sinusoidal current load cycle. It is the same results have been obtained with slight difference about MATLAB program. A de-rating factor of distribution cables is calculated in the presence of harmonic current at dry zone formation around the cable during daily load current cycle. It is concluded that the time require to dry zone formation is reduced in the presence harmonic current load cycle.

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