Applied Thermal Engineering 123 (2017) 353–364

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Thermal assessment of sheathed medium voltage power cables under non-sinusoidal current and daily load cycle

M. Rasoulpoor, M. Mirzaie *, S.M. Mirimani

Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran

ARTICLE INFO

Article history:
Received 3 October 2016
Accepted 13 May 2017
Available online 17 May 2017

Keywords:
Power cable ampacity
Thermal analysis
Derating factor
Daily load cycle
Harmonic current

ABSTRACT

In this paper thermal analysis of power cables in the presence of harmonic currents and daily load cycle is performed. A derating factor is proposed for underground power cable ampacity due to the harmonic currents and daily load cycle. Derating factor is defined based on the ac to dc resistance ratio of cable in fundamental and harmonic current conditions which are the main parameters in power cable analysis. Ac to dc resistance ratios are calculated based on the finite element simulation with consideration of skin and proximity effects. For consideration of daily load cycle, the cyclic rating factor is determined using the IEC60853 relations and also the thermal transient analysis. Possibility of cable overloading in daily load cycle of harmonic current is studied based on Arrhenius life model and also failure rate of cables. Medium voltage power cables with solid bonded metallic sheaths and circulating current losses are considered. Simulation results show the accuracy of new derating factor. Also it is shown that defined cyclic rating factor by IEC60853 is conservative and cables can be loaded higher than rated ampacity according to current condition and daily load diagram.

1. Introduction

Power cable ampacity is defined as the current carrying capability of cables without any sudden or gradually degration. Standard ampacity tables are presented based on the sinusoidal currents and 100% load factor for cables. But, sinusoidal current is rare condition in power system due to nonlinear loads, switching instruments, arc furnace devices and transients [1]. So, the accurate loading of cables in harmonic current or determination of accurate derating factor is important to avoiding the overheating of power cables.

Also, cable load is changing during operation times at a day based on the daily load cycle. So, the possibility of cable overloading should be considered in this condition. Moreover, the calculation of cable ampacity needs to determine the heat sources of power cables for thermal analysis. The resistive losses of metallic parts are the main heat sources in power cables that should be determined accurately.

Some research activities are performed to compute the power cable losses, temperature and ampacity by analytical method or finite element method (FEM). Relations are presented for losses computations of symmetric cable constructions in sinusoidal currents by IEC 60287-2-1 [2]. The presented factors in IEC are based on some limited experimental tests and for predefined constructions. Conductor losses calculations using analytical method on duct bank cables in sinusoidal current that have not any metallic layers are performed in [3]. Also, semi-empirical relations are presented for proximity losses due to an external source current. But, losses distributions are considered symmetrical which is not valid for asymmetric configurations and cables close to each other. In [4] volumetric circulating sheath loss in sinusoidal current is determined using sub-conductors method.

The fundamental of cable ampacity calculations are presented in [5]. A thorough procedure of ampacity calculation in underground cables with respect to daily load diagram is explained in [6]. Numerical thermal analysis is performed to evaluation of thermal resistance in underground power cables with different soil layers in [7]. Another, numerical thermal analysis is performed on high voltage underground cables in sinusoidal currents with consideration of multi layers soil bedding in [8]. Analytical and FEM methods are investigated for thermal analysis of underground oil filled cables in different burial depth [9]. An analytical model for the assessment of cable ampacity due to non-uniform underground temperature distribution is presented in [10]. Also a finite-element thermal model is developed for the analysis of underground cable systems in normal and emergency conditions in [11] with consideration of daily load diagram.

* Corresponding author.
E-mail address: mirzaie@nit.ac.ir (M. Mirzaie).

http://dx.doi.org/10.1016/j.applthermaleng.2017.05.070
1359-4311/

Nomenclature

List of symbols

h	harmonic order
I_h	conductor current in h harmonic order
$R_{ac,c,p}(h)$	conductor ac resistance in h harmonic order
$R_{ac,tot,p}(h)$	total cable resistance of p cable in h harmonic order
$\lambda_{1,h,p}$	armour loss in h harmonic order of p cable
$\lambda_{2,h,p}$	sheath loss factors in h harmonic order of p cable
$\Delta\theta_{h,p}$	temperature rise of p cable conductor in h harmonic order
T_1	insulation thermal resistance (K m/w)
T_2	thermal resistance of the bedding between sheath and armour (K m/w)
T_3	outer covering thermal resistance (K m/w)
T_4	thermal resistance between the cable surface and the surrounding medium (K m/w)
$W_{c,h,j}$	conductor losses of j cable in h order of harmonic current
$W_{a,h,j}$	armour losses of j cable in h order of harmonic current
$W_{s,h,j}$	sheath losses of j cable in h order of harmonic current
ρ_s	soil thermal resistivity (K m/w)
d_{pj}	distance between cable p and j
d'_{pj}	distance between j cable and image of p cable
J	current density
φ	electric scalar potential
A	magnetic vector potential
μ	permeability
ρ_e	electrical resistivity
Y_p	skin effect factor
Y_s	proximity effect factor
M	cyclic rating factor
W_t	total of joule and dielectric losses
$Ei(-x)$	exponential integral
D_e	external surface diameter of cable
δ	soil diffusivity (m^2/s)
L	axial burial depth of the cable
θ_d	temperature rise in p cable caused by the dielectric losses in p cable
$\theta_{d,pj}$	temperature rise in p cable caused by the dielectric losses in j cable
μ_c	load loss factor
$\theta_R(i)$	conductor temperature rise at time i after the application of step function of the rated current losses
$\theta_R(\infty)$	conductor steady-state temperature rise
Y_i	equivalent square current between i and i + 1 h prior to the expected time
B	activation energy to Boltzmann constant ratio
L_0	the life time at T_0 temperature
L_T	the life time at T temperature
β_t	scale parameter of cumulative probability distribution function
$L_{63\%}$	failure-time with 63.2% probability

On the other hand, one of the important results of losses calculation and thermal analysis of cables is determination of life time. The procedure for life time estimation of high voltage cables with respect to the electro-thermal stress due to the load cycle and voltage is presented in [12]. The estimation of life time of high voltage cables with consideration of voltage and load cycle in real condition is performed in [13]. Optimum placement of underground cable under sinusoidal current in a concrete duct bank is performed to maximize cable lifetime with changing in the input parameters [14].

In the abovementioned references, the calculation of ampacity and thermal analysis in harmonic condition is missed. Investigation of losses and temperature of parallel low voltage cables in non-sinusoidal currents are performed in [15]. Economical sizing of power cables in nonlinear currents is presented in [16]. For calculation of derating factor in harmonic current condition, the authors use a technique based on Neher and McGrath relations to determine the cable losses in the presence of harmonic currents in [17]. Same derating factor is used in [18] for optimal placement of underground cables in concrete duct bank. A derating factor is proposed by [19] based on the ac to dc resistance of cables which are computed by FEM. Defined derating factors are for symmetrical configuration of low voltage cable where the cable losses are equal for all three phase cables. The effect of daily load cycle is not considered on harmonic ampacity and derating factor of cables.

In this paper, definition of derating factor is developed to use for sheathed medium voltage power cables with consideration of daily load cycle. Also a new derating factor is proposed for underground cables with applying the thermal effects of adjacent cables. Derating factor is defined based on ac to dc resistance ratio of power cables in different harmonic signatures. Ac to dc resistances ratios of cables are calculated based on FEM simulations. Transient thermal analysis is performed for determination of cable temperature as well as cyclic rating factor based on IEC standard. So, the possibility of cable overloading is investigated based on Arrhenius life model and cable failure rate. Different cross sections of medium voltage cables with metallic sheaths are considered in the simulations. Metallic sheaths are solidly bonded and circulating current losses are considered. Accuracy of proposed derating factor and cyclic rating factor using transient temperature is investigated by calculation of cable ampacity in harmonic currents and the presence of daily load diagram. The sections of paper are constructed as below.

The procedure to determine cable derating factor in steady state load condition is described in Section 2. In Section 3 the calculations of derating factor in daily load cycle condition as well as the cyclic rating factor are described. The thermal analysis and simulation results are presented in Section 4. Conclusion remarks are stated in Section 5.

2. Thermal analysis in the steady state load condition

Harmonic currents cause the reduction in the cable ampacity than sinusoidal condition. So, calculation of derating factor is important to prevent the overheating of cables. In this section the calculation of derating factor is described in the steady state load conditions.

2.1. Ampacity derating factor in the presence of harmonic currents and steady state load condition

In this paper the medium voltage cable are considered and the cable dielectric losses is neglected for these cables. However generally in the calculation of derating factor the dielectric losses are not inserted, because the assumption of constant applied voltage and hence constant dielectric losses.

Cable losses can be described as the ratio of ac to dc resistance. This factor indicates cable variation resistance in harmonic condition. Cable resistive losses can be computed in the presence of harmonic currents using FEM. It is assumed that harmonic current in three phase system to be balanced as follows: