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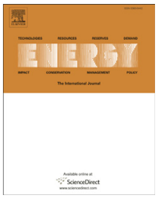

Heat transfer analysis of metal oxide surge arrester under power frequency applied voltage

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ABSTRACT

Electro-thermal model of metal oxide surge arrester based on adaptive method has been proposed in this paper. Finite element method has been used to model surge arrester. Power loss, which is major parameter in electro-thermal analysis, has been estimated as a heat source in proposed model using artificial neural network and adaptive network based fuzzy inference system. In addition to voltage and temperature, operating history is also an important factor that must be considered in power loss estimation process. In order to formulize surge arrester performance history, degradation factor has been suggested as a new index in this paper. Therefore, voltage, temperature and degradation factor have been used as inputs in artificial models. So as to train the artificial neural network and adaptive network based fuzzy inference system, experimental results have been obtained by laboratory tests on new and utilized surge arresters varistors. In this regards, high voltage experimental setup, chamber and an oven have been prepared to acquire modeling data. Also, the results of infrared thermal camera have been used to validate the results of proposed adaptive electro-thermal model. Moreover, convection and radiation as effective factors in surface to ambient heat transfer have been studied and compared.

1. Introduction

Various methods such as laboratory tests, electrical circuit or computational simulation can be used to analyze thermal behavior of MOSA (metal oxide surge arrester) [1]. Laboratory tests require expensive equipment and thus, these tests are not usually economic. Therefore, developed electro-thermal modeling of MOSA is useful for the realization of electrical and thermal variations and design stage [2].

In electrical equivalent circuit, current, voltage, capacitor and resistor have been used to represent the heat flow and electro-thermal parameters. The values of mentioned parameters have been achieved by experimental tests [3]. On the other hand, FDM (finite difference method) [2,4] and FEM (finite element method) [5,6] have been suggested as computational simulation methods. Modeling based on computational method is accurate, flexible and fast and also it is suitable for design of MOSA with complex geometry and different operation condition [1].

Electro-thermal model consists of electrical and thermal models. Heat generation based on electrical power loss is the aim of electrical model. And also thermal model has been used to analyze the heating time trend of the MOSA parts [7]. According to MOSA operation region, power loss should be modeled to achieve the heat source. In lightning and switching surge discharges, optimized electrical model and empirical relationship can be used to calculate input energy to the varistor [8,9]. But, energy input in power frequency applied voltage is a complex function of voltage, temperature and operating history [3]. Therefore, accurate power loss modeling is very important to model the electrical part of MOSA, properly. Varistor construction materials [10], operating history [11] and temperature [12] are three main factors that cause power losses changing.

Various methods have been proposed to model the electrical power loss. In Ref. [13], Power loss has been modeled as a continuous function of temperature at constant voltage level by the empirical data. Interpolation between each point of V–I–T (voltage–current–temperature) characteristic is suggested in Ref. [14] by the logarithmic function. In Ref. [15] a lookup table based on voltage–current–temperature curve has been used to compute power loss curve. Also, ANN (artificial neural network)) was used to estimate power loss characteristics of ZnO (zinc oxide) varistors based

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Nomenclature

Abbreviations

Adaptive network based fuzzy inference system	ANFIS
Artificial neural network	ANN
Current Orthogonality Method	COM
Degradation factor	DF
Finite difference method	FDM
Finite element method	FEM
Fuzzy inference system	FIS
Fuzzy c-means clustering	FCMC
Grid partitioning	GP
Membership function	MF
Metal Oxide surge arrester	MOSA
Partial differential equations	PDE
Subtractive clustering	SC
Two dimensional	2-D
Voltage ratio in reference and rated point for virgin varistors	VR_V
Voltage ratio in reference and rated point for degraded varistors	VR_D
Zinc oxide	ZnO

Symbols

Ambient temperature	T_{amb}
Artificial neural network output	y_d
Centigrade	°C
Current	I
Conductive flux vector (W/m^2)	q
Density (kg/m^3)	ρ
Emissivity between the side surface and the environment	ε
Firing strength of a fuzzy rule	w_i
Heat source (W/m^3)	Q(r)
Heat transfer coefficient ($W/m^2\ ^\circ C$)	h
Inputs vector	X
Inputs of neurons	u_j
Membership of node	μ_{A_i}
Normal vector of the boundary	n
Net influx from radiation (W/m^2)	q_r
Output of the neuron	y_j
Overall output of ANFIS	$f\overline{w'}$
Power loss	p
Rated voltage	V_{rat}
Reference voltage	V_{ref}
Resistive component of leakage current	i_r
Stefan–Boltzmann's constant	σ
Standard deviation	σ_{sd}
Synaptic weight vector	w
Square error	E
Specific heat capacity at constant pressure	C_p
Temperature	T
Thermal conductivity ($W/m.\ ^\circ C$)	k
Time (s)	t
Threshold value of neuron	a_j
Target output	TO_d
Velocity vector	u
Voltage	V, v

on temperature and applied voltage [5]. Identification power loss characteristic of MOSA with different characteristics is not possible by the above mentioned methods. In other words, operating history has very important role to identify accurate voltage and current (V–I) characteristics and power losses which has been ignored in previous literature.

Thermal properties of MOSA were represented as a simple analog model in Ref. [3]. The model parameters, used for steady-state and transient simulation of arrester performance, could be determined analytically from physical dimensions of a particular surge arrester unit or derived by experimental measurements. Electro-thermal model for MOSA analysis in polluted condition was proposed in Ref. [16]. In this model, thermal capacity of the metal plates in the varistor column and the temperature dependence of the ZnO specific heat were added. Also in Ref. [7], mathematical model of MOSA was implemented to simulate the arrester electro-thermal performance under contamination and dampening environmental condition. Electrical and thermal parameters of each part were modeled as separate section. The accuracy of this model was improved as a result of this condition. In addition, a computational electro-thermal model for complete metal-oxide surge arrester was presented based on the implicit form of the finite-differences method [2].

In this paper, 2-D axial symmetric electro-thermal model using finite element method has been proposed. Power loss characteristic as heat source has been improved by adding a new factor (operating history) in computation process. *DF* (Degradation factor) as a new index has been used to represent operating history of MOSAs in power frequency applied voltage. Therefore, the power loss has been modeled by an adaptive network based fuzzy inference system and ANN. Applied voltage, temperature and operating history are the main parameters which have been considered as inputs in ANFIS and ANN. Based on proposed DF, electrical power loss of MOSAs can be modeled by considering degradation effect. In order to consider DF index, several varistors, which were collected from new and used MOSAs, have been studied in laboratory. Moreover, electric and thermal conductivity and heat capacity have been considered as electric field and temperature dependent parameters. For validation of the proposed electro-thermal model, the results have been compared with the thermal camera results in different applied voltages. In addition, the effects of convection and radiation on heat transfer have been analyzed using electro-thermal model. Finally, the variation of heat transfer coefficient has been discussed as major factor in convection. As mentioned above, Fig. 1 has been shown to illustrate the different parts of this paper. This figure consists of three subsections as follow:

(A) : preparing the power loss characteristic
(B) : preparing the electro-thermal model based on FEM
(C) : coupling the electrical and thermal models and analyzing the heat transfer

2. Power loss modeling

2.1. Power loss characteristics: measurement

Power loss has been affected by temperature, operating history and the material variation of varistor. To investigate the influence of all aforementioned factors, experimental setup has been arranged. Fig. 2 shows the schematic view of voltage and leakage current of measurement circuit in different temperature and laboratory setup. The experimental setup consists of a high voltage transformer, high voltage probe, data acquisition systems and oven.