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ScienceDirect
Mathematics and Computers in Simulation 130 (2016) 81–94
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original articles

Simplified simulation model of continuously transposed cable for linear and nonlinear buckling analysis

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Received 24 September 2014; received in revised form 20 April 2015; accepted 17 June 2015
Available online 26 June 2015

Abstract

Continuously transposed cable (CTC) is a multistranded conductor mainly for application in power transformers. As its structure is complicated a simplified simulation model and an easy analytic model for the buckling analysis of transformer coils are investigated in this paper. In the simplified models the transposition of the strands is neglected leading to an easy rotation symmetric cross section. These simplified models are compared to detailed models using finite element analysis (FEA) based linear and nonlinear buckling simulations. Furthermore analytical approaches are adopted from the buckling-behavior of a circular arch for the use with CTCs. All models are compared with respect to their critical buckling load for some typical winding and CTC dimensions varying between 11 to 41 strands. The maximum deviation between detailed and simplified FEA based CTC models for both linear and nonlinear buckling analysis lies below 13%. The deviations for the analytic approaches are with a maximum of 22% higher but serve to verify the trends deduced from the simulation results.

Keywords: Continuously transposed cable; CTC; Power transformers; Linear & nonlinear buckling; Finite element analysis

1. Introduction

1.1. Short circuit problem of power transformers

Short circuit events in power transformers can lead to serious damage on windings or in the worst case, to a total loss of the transformer. Especially, high radial electromagnetic forces, as a result of short circuit currents applied to the low voltage winding, may lead to the so called radial buckling: Parts of the winding collapse and buckle between the radial supports under the influence of the radially inwards directed force [5]. In order to analyze the radial buckling strength of windings, many approaches have been investigated. Usually the problem is considered as uniformly compressed circular arch with hinged ends [8,7]. For the conductors flat magnet wires are often considered. The authors of [1] for example analyze spiraling phenomenon in helical transformer windings based on flat wires. In [2] a buckling strength analysis for a winding built with an epoxy-bonded continuously transposed cable is proposed. Due to the

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http://dx.doi.org/10.1016/j.matcom.2015.06.005

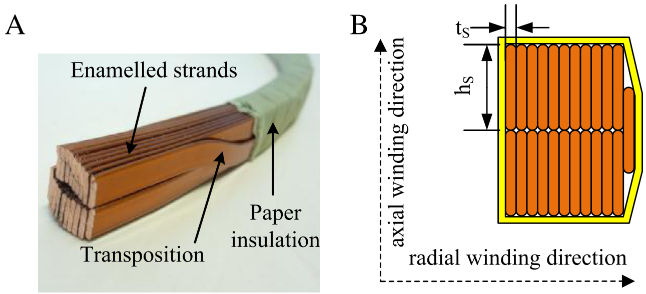

Fig. 1. (A) CTC with 21 strands, (B) CTC cross-section.

epoxy-bonding, the authors simplify the CTC as a massive conductor with same cross-section outer dimensions. For a non epoxy-bonded CTC the hint to use an equivalent cross section corresponding to a strand can be found in [2] without further proofs. In this paper a similar approach to describe the buckling behavior of CTC based windings will be developed and verified by the use of detailed FEA models.

1.2. Principle structure of CTCs

CTCs are typically used for power transformer windings to increase efficiency compared to the paper-insulated flat magnet wires. CTCs consist of rectangular shaped, enamel coated copper strands, which are arranged in two stacks (Fig. 1(A)). The number of strands is usually odd and often lies between 11 and 81. By dividing the copper cross-section into single strands CTC based windings mainly reduce eddy current losses. The strand thickness t_S in radial direction is much lower than its height h_S (Fig. 1(B)). The reason for this is the reduction of loop voltages as a result of radially varying magnetic stray fields. Loop voltages also arise between the strands as they are connected in parallel at the winding endings. To compensate for the corresponding losses, the strands are transposed with each other: After a fixed distance called transposition-pitch the two radial outer- and innermost lying strands change their stack. Due to these regular changes in radial position each strand is exposed to the same average stray field along one winding turn and the induction of loop voltages is avoided [6]. For electrical insulation between turns the CTC is wrapped by several layers of paper.

2. Linear buckling: Analytic approach

2.1. Buckling of a circular arch

For radial buckling analysis the low voltage winding of a power transformer is usually simplified as circular arch supported by spacers. This kind of support is assumed to be hinged [8,7]. The radial electromagnetic force component can be converted to a uniform radial line load q on the outer arch surface, Fig. 2. For such a two hinged circular arch, the critical buckling load $q_{\text{crit},n}$ can be derived according to [3] to:

$$q_{\text{crit},n} = \frac{E \cdot I}{R^3}\left[\left(\frac{n \cdot \pi}{\alpha}\right)^2 - 1\right] \quad \text{for } n = 2, 4, \ldots. \tag{1}$$

The number n describes the count of buckling halfsine waves within the circular arch with its opening angle α and mean radius R. n has to be an even number, as deflections outward tend to extend the arch while inward directed deflections shorten the arch. In sum they have to compensate for each other. The remaining parameters are Young's modulus E and second moment of inertia I. For a cross-section according to Fig. 2 and the load acting in radial direction I can be calculated to:

$$I = \frac{1}{12} \cdot h \cdot t^3. \tag{2}$$

If the electromagnetic force exceeds the critical buckling load for the lowest mode with $n = 2$ the winding collapses. It is important to recognize that linear buckling is an instability event where only the geometry fails. The material is assumed to behave linearly, so that the collapse is not a result of reaching plastic deformation. As the center