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Survey on Transformer Winding Deformations, Causes, Monitoring and Mitigation

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Abstract

Transformers are the most widely used and expensive components of power systems. Short-circuit forces are one of the main stresses experienced by transformers during their life cycle. The persistent increase in the demand for electricity has resulted in the increment of more generating units and interconnections, making the short-circuit duty of transformers more hard. Under short-circuit conditions, the currents in the high-voltage and low-voltage windings can reach 10-30 times their rated values. The inrush current lasts longer and occurs more frequently with respect to the short-circuit current; an inrush current with a peak value of 70 percent of short-circuit current causes the same mechanical harm with respect to short-circuit events. Transformers should be designed to withstand these conditions and to prevent failures and service interruptions. To the best of our knowledge, there is a lack of a comprehensive survey on transformer winding deformations, causes of these deformations, monitoring of deformations, and mitigation techniques which is presented in this paper.

Keywords: Transformer, Short-circuit Force, Winding Deformation, Radial Forces, Axial Forces, Inrush Current, Monitoring, Mitigation.

Introduction

Transformers are the most widely used and expensive components in a power system and play a vital role in power system reliability [1]-[10]. Nowadays, without the transformers, it is impossible for the customers to receive electricity from power systems [1]-[2], [5], [11]-[14]. There are nearly five to ten transformers between the power plant and the power utilizer [2], [5]. Transformers have inherently high efficiencies with respect to the other electrical power apparatuses, but the huge number of installed transformers in a power network causes huge energy losses during their long lifespan [15]-[20].

Transformer failure may occur as a result of different causes and conditions [21]-[47]. Growing age and growing loading of the existing transformer population (30-40% are older than 25-30 years and loading has been considerably increased e.g., in the United States, from an average of 60% to > 80% in the past 15 years) stipulate the need for expert diagnosis [44]. One way to minimize failure probability is the analysis of old failures and their conditions in order to understand the reasons for severe failures and to improve maintenance procedures by means of this knowledge [45]. There are various causes of transformer failures during operations, such as [48]-[52]:

- Electrical disturbances
- Deterioration of insulation
- Lightning
- Inadequate maintenance

- Loose connections
- Moisture
- Overloading

With appropriate monitoring of the transformer (on-line or off-line) with different tools and techniques which have been introduced in the literatures, failure rate of transformers will be decreased. Some of these techniques and tools are [51]-[81]:

- Dissolved gas analysis (DGA)
- Frequency response analysis (FRA)
- Partial discharge (PD) analysis
- Short circuit impedance method
- Transfer function method
- Vibro-acoustic method
- Fiber bragg grating (FBG) sensors
- Thermal modelling
- bushing monitoring
- Capacitive sensors
- Tank vibration
- Winding stray reactance
- Current deformation coefficient
- Gas Chromatography
- etc.

Short-circuit forces are one of the main stresses that a transformer experiences during its life cycle [81]. Under short-circuit conditions, currents in the high-voltage and low-voltage windings can reach 10-30 times their rated values [34]-[36]. To avoid the harm caused by these forces, the windings of the transformer were mechanically supported and pre-pressed using bandages, wedges, and heavy bolts. The dimensioning criterion for these support structures is usually the force caused by the highest possible current peak, which typically occurs under short-circuit conditions [32].

The continuous increase in the demand for electrical power has resulted in the addition of more generating capacities and interconnections in power systems, which have contributed to an increase in the short-circuit capacity of networks, making the short-circuit duty of transformers more severe [1], [28]-[31]. The inrush current lasts longer and occurs more frequently with respect to the short-circuit current; an inrush current with a peak value of 70 percent of short-circuit current causes the same mechanical harm with respect to short-circuit events [1], [28]-[29], [32], [35]-[36]. The mechanical design of windings and support structures should be such that they can withstand these conditions and prevent failure and service interruption [20]. Based on IEC 60076-5, transformers should withstand short-circuit events for 2 two seconds [30]. In the case of YNd-connected transformer, the single-line-to-ground short-circuit is more severe. Except for such specific case, the three-phase short-circuits are the most severe. Hence, it is common practice to design a transformer that can withstand three-phase short-circuit at its terminals. The other windings were assumed to be connected to constant voltage sources [1].

High temperature superconducting (HTS) transformers are more vulnerable to mechanical stresses, with respect to the conventional copper winding transformers, due to lower mechanical strength of the superconducting windings with respect to copper [28], [31], [33].

The first international survey on large power transformer failures was published in 1983 summarizing the results of the analysis of transformers that failed in the period 1968 to 1978 [48], this survey concluded that the average failure rate of transformers may be regarded as 2% across all voltage categories. Since then, this statistic has become an international benchmark in the transformer industry for the failure rate performance of transformers [50].

In [69], a review of PD detection in an oil-immersed power transformer using FBG sensors has been presented. An overview of the current state-of-the-art in vibro-acoustic condition monitoring of power transformers with the focus on OLTC and transformers' winding/core diagnostics has been presented in [70]. Review of chemical and electrical diagnostic methods for assessing insulation condition in aged transformers has been presented in [115]. Survey on failures in large power transformers has been presented in [48]. Standardized survey of transformer reliability has been presented in [50].

To the best of our knowledge, there is a lack of a comprehensive survey on transformer winding deformations, causes of these deformations, monitoring of deformations, and mitigation techniques which is presented in this paper.

Causes of Winding Deformation

As causes of winding deformation we can say:

There are various types of short-circuit faults which result into very high over currents. Single line-to-ground fault, line-to-line fault with or without simultaneous ground fault and three-phase fault with or without simultaneous ground fault. When the ratio of zero-sequence impedance to positive-sequence impedance is less than one, a single-line-to-ground fault results in higher fault current than a three-phase fault [1].

Electromagnetic forces on transformer windings which are very significant in short-circuit events are the main cause of the deformation and consequently failure in transformer windings [1], [81]. Also, during the transportation of transformer to its installation place and earthquake, winding deformation may be occurred [32]-[38], [81]-[84].

The short-circuit forces are resolved into the radial and axial components simplifying the calculations. The approach of resolving them into the two components is valid since the radial and axial forces lead to the different kinds of stresses and modes of failures [1]. Different methods are available for the calculation of different components (radial and axial) of the electromagnetic forces, they are [36]-[37]:

- Stored magnetic energy method
- Image method
- Roth’s method
- Rabin’s method
- Finite element method

The transformer windings along with the supporting clamping structure form a mechanical system having mass and elasticity. The applied electromagnetic forces are oscillatory in nature and they act on the elastic system comprising of winding conductors, insulation system and clamping structures. The forces are dynamically transmitted to various parts of the transformer and they can be quite different from the applied forces depending upon the relationship between excitation frequencies and natural frequencies of the system. Thus, the dynamic behavior of the system has to be analyzed to find out the stresses and displacements or deformations produced by the short-circuit forces [1].

IEC 60076-5 [30], has been provided formulas for the calculation of the winding temperature after the short-circuit event. If the transformer windings have been made by copper conductors, after 2 seconds short-circuit event, the maximum temperature of the transformer windings should not exceed 250^{o} C. this temperature for the transformers which are made by aluminum conductors, is 200^{o} C [30]. The above mentioned formulas for the copper winding transformers and aluminum winding transformers have been presented in (1) and (2), respectively.

$$\theta_1 = \theta_0 + \frac{2}{\frac{101000}{J^2 t} - 1}\left(\theta_0 + 235\right) \quad (1)$$

$$\theta_1 = \theta_0 + \frac{2}{\frac{43600}{J^2 t} - 1}\left(\theta_0 + 225\right) \quad (2)$$

Transformer winding deformation types which are caused by radial, axial and combined components of forces can be categorized as below [51]:

- Deformation types caused by radial component of forces
  - Forced buckling
  - Free buckling (hoop buckling)
  - Hoop tension (stretching)
  - Relaxation buckling
- Deformation types caused by axial component of forces
  - Tilting (cable-wise tilting, strand-wise tilting)
  - Conductor bending between radial spaces
- Deformation types caused by combined forces
  - Spiraling
  - Telescoping
  - Twisting

Some of modes of the winding deformations are presented in Fig. 1 to 4. These forms are:

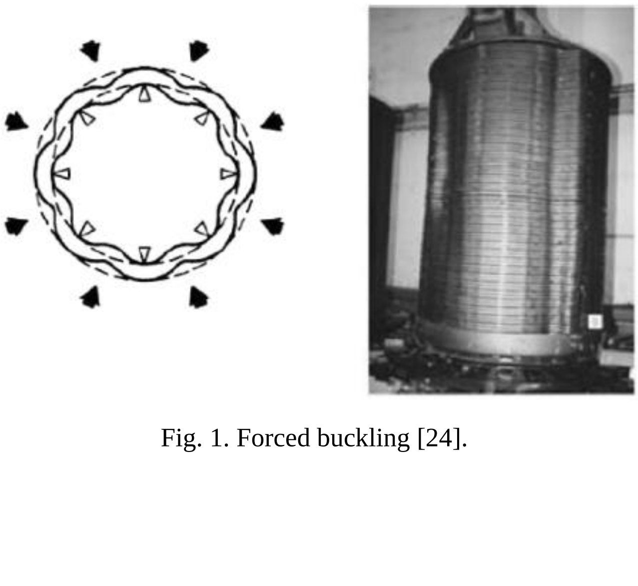

Fig. 1. Forced buckling [24].

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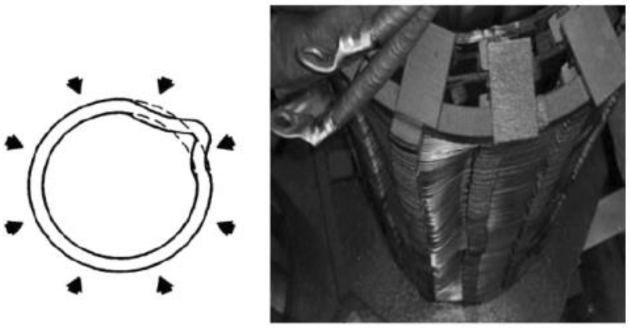
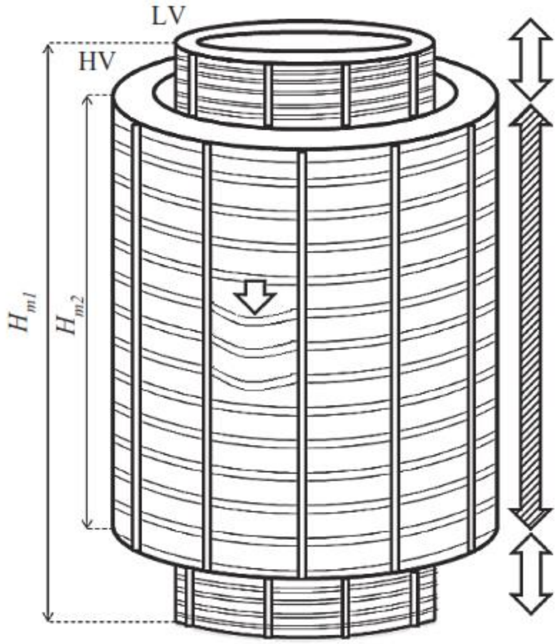
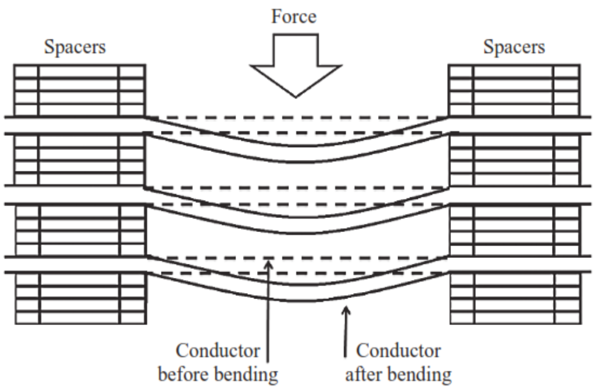


Fig. 2. Free buckling [24].

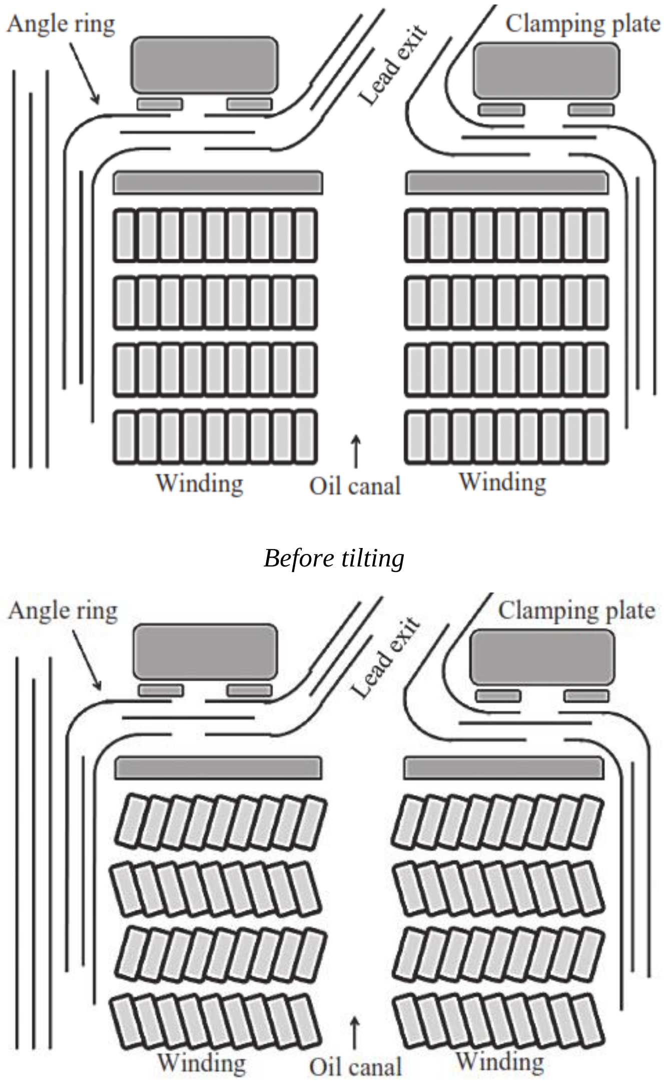


Bending (side view)



(a) Bending (close view)

Fig. 3. Bending [51].



Before tilting

After tilting

Fig. 4. Tilting [51].

Monitoring

As monitoring methods for winding deformations we can say:

Fault diagnosis based on online monitoring has been well considered since the last decade. Approaching to more smart methods brings more challenges.

Advanced online methods for diagnosis of winding deformations are [81]-[120]:

- Transformer tank vibration method
- ultrasonic method
- short-circuit impedance method
- transfer function method
- using leakage parameters

Some examples have been shown in Fig. 5 to Fig. 7.

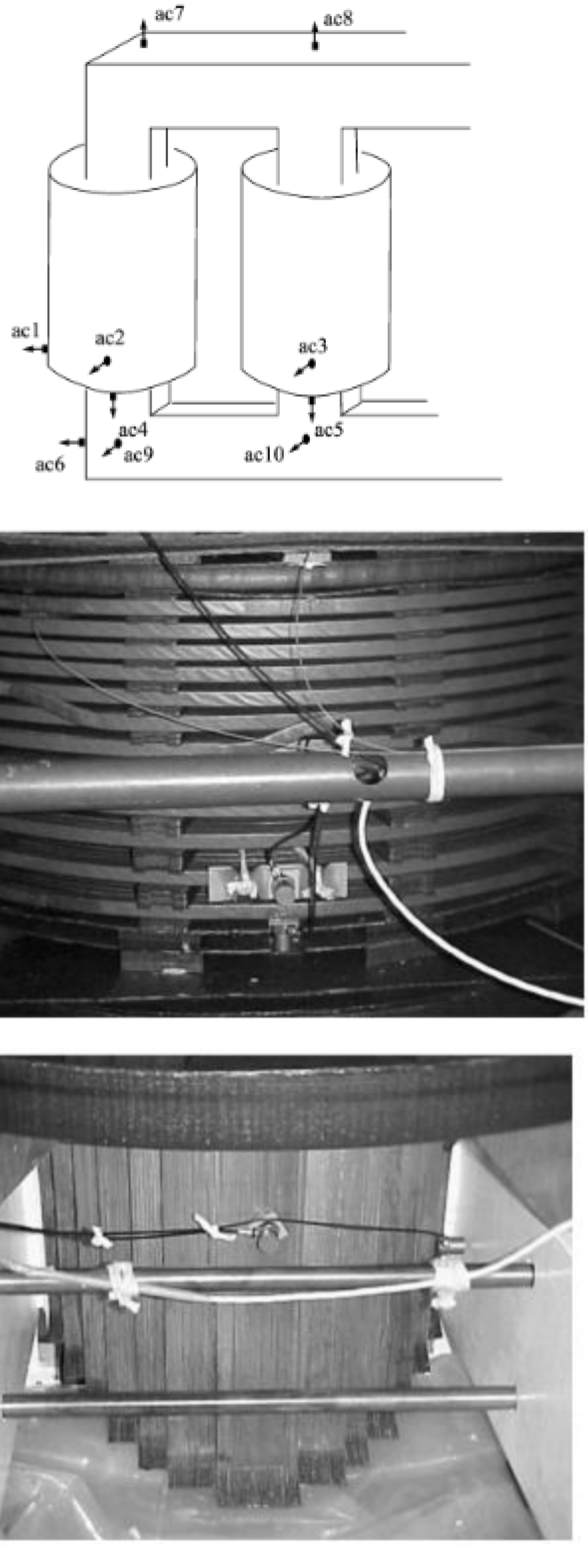


Fig. 5. Internal accelerometers installed on the winding and core [86]-[87].

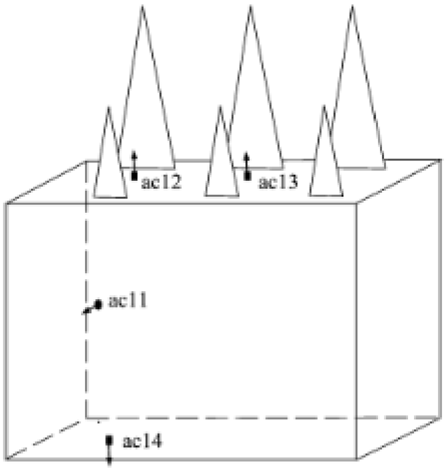


Fig. 6. Accelerometers installed on the transformer tank [86].

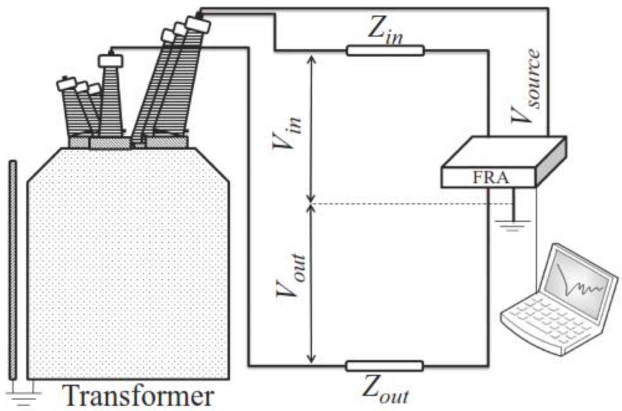


Fig. 7. Typical experimental set-up for FRA testing [51].

Measuring of short-circuit impedance of a transformer and comparing the achieved value with the previous values or factory test is very useful for diagnosis of winding deformation. In another words, short-circuit impedance method is based on the comparison during time. Short-circuit impedance is dependent to transformer configuration and distance between windings. Over 3% change in the short-circuit impedance in a transformer should be considered [109].

Transfer function is a method for description of behaviour of a system. This method has been increasingly used for diagnosis in power equipment, especially for diagnosis of winding deformation in transformers [110]-[111].

Mitigation

As mitigation methods for winding deformations we can say:

In [28], as shown in Fig. 8, optimal design of a flux diverter for an HTS transformer has been performed. The minimization of the axial short-circuit electromagnetic force density on HTS transformer windings has been employed as the objective function. The optimal dimensions, placement parameters, and permeability of the flux diverter have been determined. Finite element method (FEM) modeling and simulations have been used for verification. FEM showed 60.75 percent reduction in the maximum value of axial short-circuit force density.

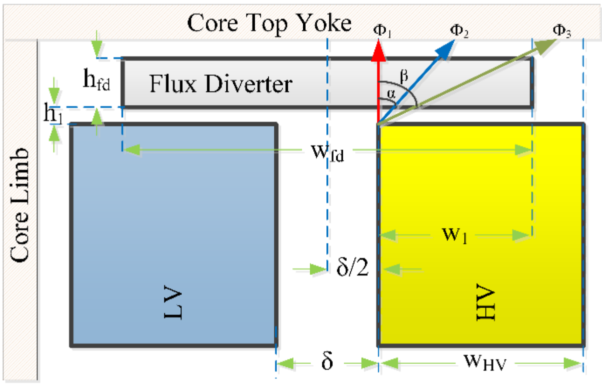


Fig. 8. Application of flux diverter for short-circuit force reduction [28].

In [31], [121] as shown in Fig. 9, optimal design of auxiliary windings has been performed for an HTS transformer. It has been shown that utilizing these optimum auxiliary winding; the leakage fluxes, the radial and the axial components of the short-circuit forces have been reduced by 16.13%, 16.11% and 7.97%, respectively.

The axial forces applied to the HV winding at 5th, 10th and 30th inrush current peaks are about 29.9, 84.3 and 91.8 percent larger than the corresponding forces at 5th, 10th and 30th short-circuit current peaks, respectively; however, the radial force on the HV winding in inrush current case is smaller than the corresponding force in short-circuit condition. Concluding from the results, to avoid serious risk on damage of insulation within transformers which are subject to frequent energizations, countermeasures should be taken, e.g., sequential phase energization might be applied [32].

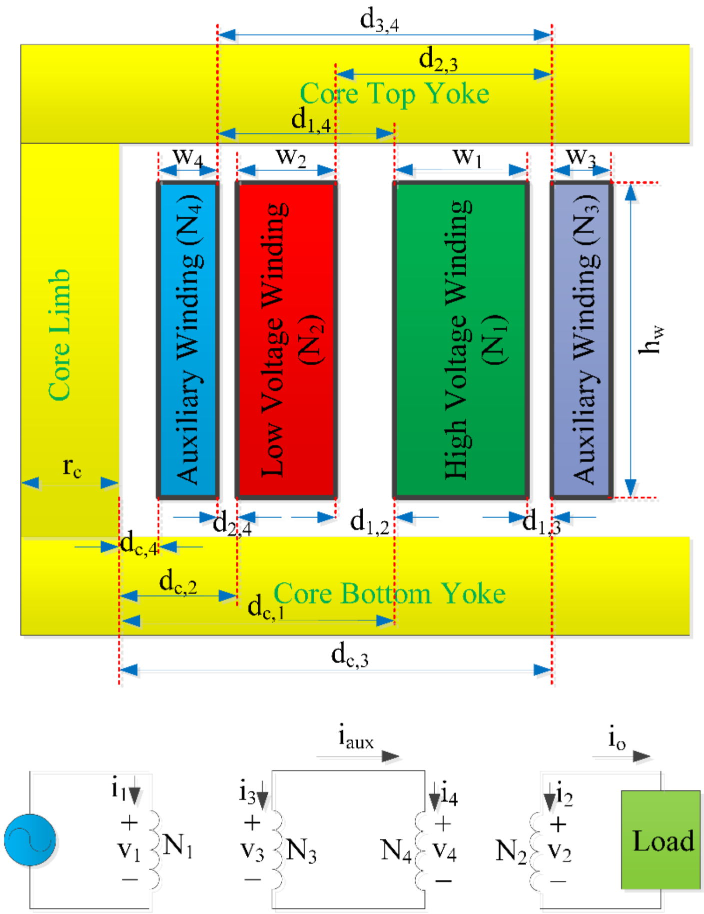
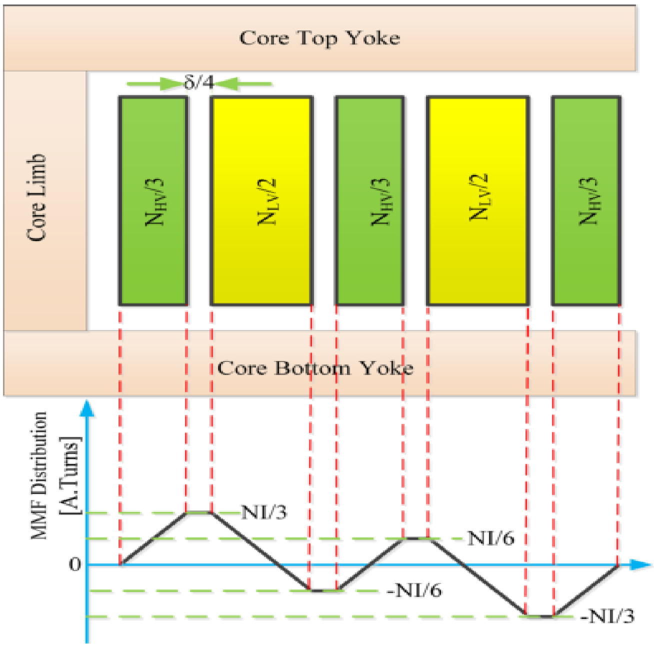
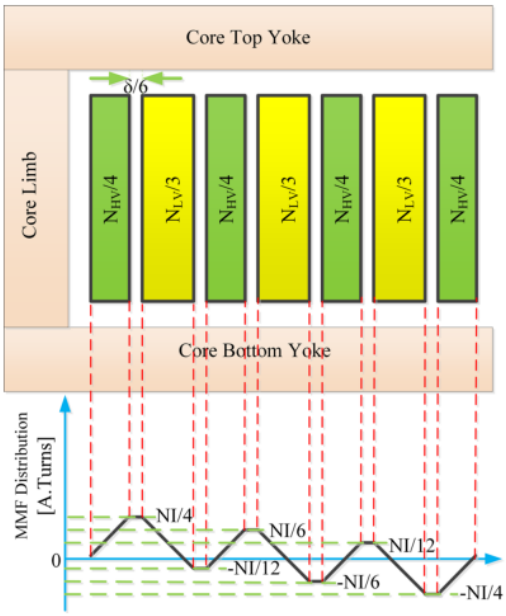


Fig. 9. Application of auxiliary windings for short-circuit force reduction [31].

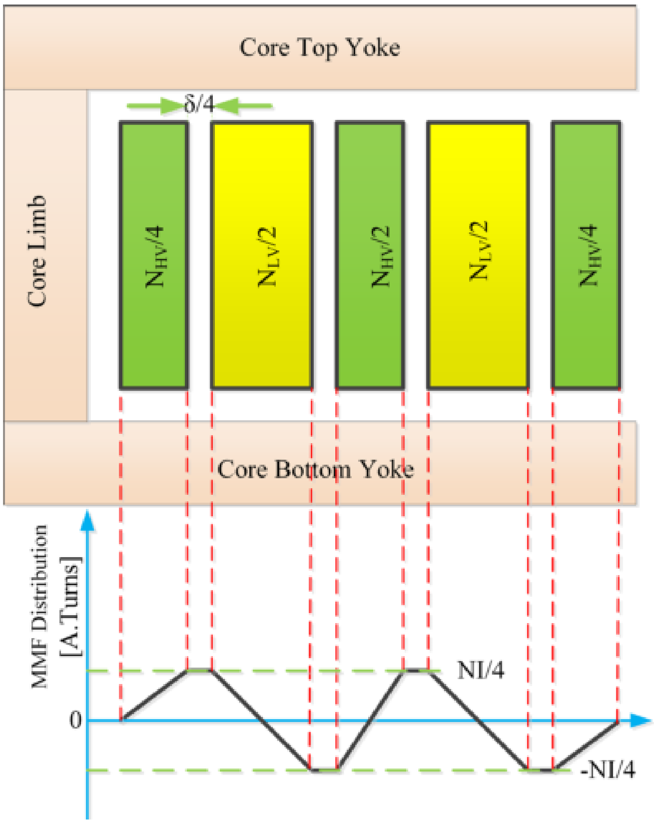
An analytical method for the determination of optimum distributive ratios for asymmetrical multi-segment windings is presented in this paper. Employing the optimum distributive ratio (k = 1/12) and using the analytical method when an asymmetrical HLHLH configuration is employed, a 75 percent reduction, and when an asymmetrical HLHLHLH configuration is employed, an 83.3 percent reduction in the radial short-circuit forces is determined with respect to the LH winding configuration short-circuit forces. These reductions for the axial short-circuit forces of the HLHLH and HLHLHLH configurations are 69.7 percent and 79.1 percent, respectively [33]. Distribution of magneto motive force (MMF) around the windings in the symmetrical five-segment, symmetrical seven-segment, asymmetrical five-segment and asymmetrical seven-segment windings have been shown in Fig. 10.



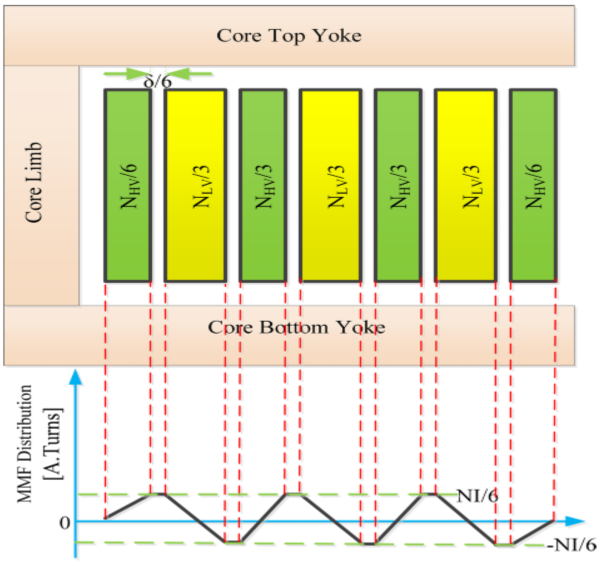
(a)



(b)



(c)



(d)

Fig. 10. Application of multi-segment windings for short-circuit force reduction. (a) symmetrical five-segment, (d) symmetrical seven-segment (c) asymmetrical five-segment, (d) asymmetrical seven-segment [33].

Conclusion

The persistent increase in the demand for electricity has resulted in the increment of more generating units and interconnections, making the short-circuit duty of transformers more hard.

Transformer failure may occur as a result of different causes and conditions [21]-[47]. Growing age and growing loading of the existing transformer population (30-40% are older than 25-30 years and loading has been considerably increased e.g., in the United States, from an average of 60% to > 80% in the past 15 years) stipulate the need for expert diagnosis.

Under short-circuit conditions, the currents in the high-voltage and low-voltage windings can reach 10-30 times their rated values. The inrush current lasts longer and occurs more frequently with respect to the short-circuit current; an inrush current with a peak value of 70 percent of short-circuit current causes the same mechanical harm with respect to short-circuit events. Transformers should be designed to withstand these conditions and to prevent failures and service interruptions. To the best of our knowledge, there is a lack of a comprehensive survey on transformer winding deformations, causes of these deformations, monitoring of deformations, and mitigation techniques which is presented in this review paper.

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