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EFFECTS OF DC-BIAS ON LOSS DISTRIBUTION OF MODEL TRANSFORMER CORE

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By means of the rise-of-temperature method, the regional distribution of the local building factor *BF* was measured at 23 positions in a model transformer core assembled from grain oriented SiFe. In a systematic way, the case of mere AC excitation was compared with that of additional DC excitation in the middle S-limb. The mere AC case showed lowest *BF* in the central regions of the outer limbs, highest one in the corners and – in special – in the T-joints due to rotational magnetization (RM). DC bias yielded strongly increased *BF* in regions of alternating magnetization and lower ones in regions of RM, a tendency which is interpreted through domain theory. Energetic relevance is not expected for the case of geomagnetically induced currents, strong effects being restricted in time. On the other hand side, weak bias of long term may deteriorate the performance of 5-limb 3-phase cores and – in special – that of 1-phase cores.

Keywords: transformer cores, magnetic losses, DC bias, magnetic domains, energy problems

1 INTRODUCTION

In increasing ways, worldwide globalisation includes intercontinental distribution of electric power which comprises the rising introduction of high voltage direct current (HV-DC). The latter shows the advantage of lowered energy losses. However, the combination of AC and DC power equipments yields the problem that AC machines like power transformers may be affected by DC bias. Possible reasons (Fig. 1) are imperfect thyristor/transistor sets, or DC of the earth surface passing into grounded transformers - analogous to geomagnetically induced currents (GICs) which may even cause destruction of the transformer. As a severe example, in 1989 a field variation of 1 μT was sufficient to destroy a large US nuclear plant transformer and to cause global black-outs [1,2].

As well known, DC-bias of transformers may yield increases of all three excitation currents, stray fields and audible noise. On the other hand side, very little is known about effects on the magnetic state of the laminated core of the machine. Earlier, we have simulated bias on Rotational Single Sheet Tester (RSST) samples of grain oriented core steel, the results revealing distinct loss increases [3]. The present paper gives a first report on effects on the regional distribution of losses in a completed model core.

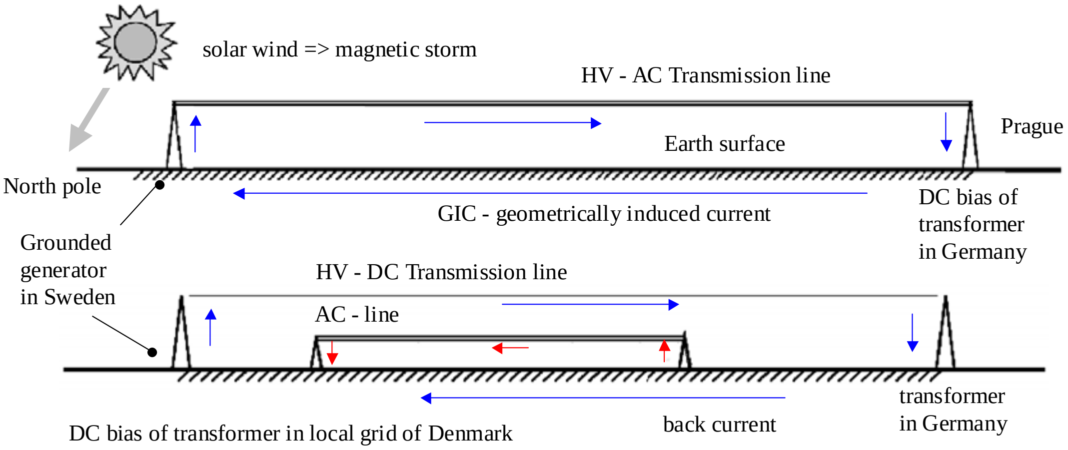

Fig. 1. Schematic outline of three possible sources of DC bias of cores of grounded transformers. (i) Geomagnetically induced currents (GICs) may enter HV-AC lines and return to earth through transformers. (ii) In the same way, HV-DC through the earth may enter in local HV-AC lines. (iii) Rest DC may result from conversion processes.

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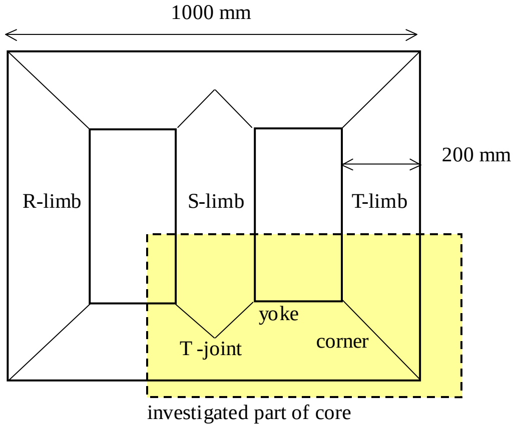

Fig. 2. Investigated model core. Analyses of loss distributions were performed for the indicated part of the core

2 EXPERIMENTAL

Experiments were conducted on a 3 phase, 3-limb model transformer core magnetized with 1.7 T (50 Hz). The core size was 1 m × 1 m (Fig.2). It was stacked from 56 layers of grain oriented SiFe-sheets (30M5), the sheet width being 200 mm.

Local loss measurements were carried out by means of a thermistor sensor. It was located at 23 inner core positions through 2 mm wide holes of the about 3 mm thick outermost core package. This procedure offers information about the - mainly relevant - core interior. It eliminates side-effects of surface stray fields, and it considers the experience of decreased flux density in outermost laminations. For each position, the core was magnetized for 30 s – a rather short duration which reduces global heat-up of the core. Further, considering the velocity of heat transport in SiFe, it yields a regional average of some centimeters which coincides with the average distance of the 23 positions of measurement.

Superposition of DC excitation on AC excitation was restricted to the S-limb. Rather weak bias was simulated by adjusting the DC/AC-excitation ratio $r_{DC} = (N_{DC} I_{DC})/(N_{AC} I_{AC})$ close to 0,4 (with N_{DC} the number of DC windings, I_{DC} the DC-bias current intensity of the S-limb, N_{AC} the total number of AC windings and I_{AC} the mean peak value of AC current intensities for $r_{DC} = 0$, *ie* for the unbiased case. In addition, the case of strong bias was tested with $r_{DC} = 2.7$.

3 RESULTS

Figure 3a shows results of measurement for the mere AC-case. Data is given for the so-called local building factor $BF = P_{LOC} / P_{REF}$ with P_{LOC} as the loss value as registered at the individual, tested position. P_{REF} is the loss value as measured at the reference point "REF" in the middle of the T-limb, a position where nominal losses of material can be expected in good approximation.

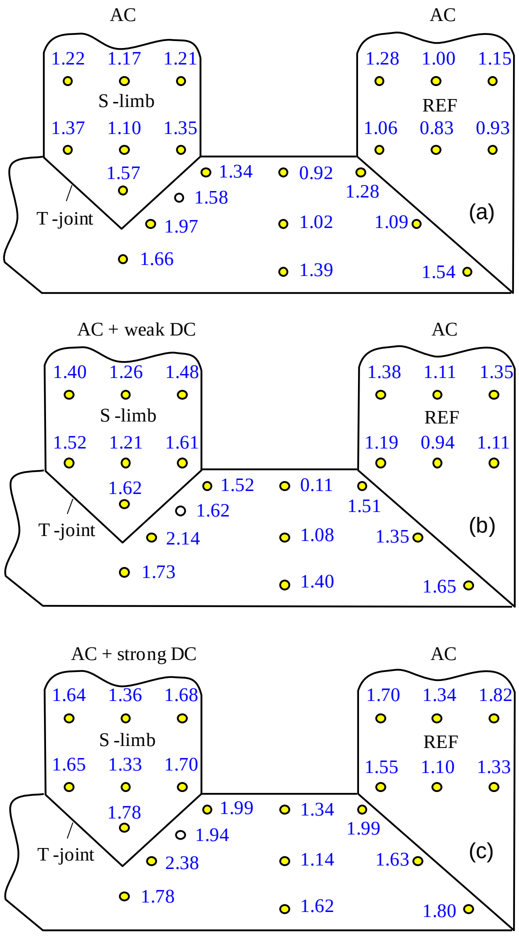

Fig.3. Local building factors for 23 positions of the core magnetized with 1.7 T. (a) Mere AC excitation. (b) Additional DC excitation in the S-limb with $r_{DC} = 0.4$. (c) With $r_{DC} = 2.7$.

Outer limbs yielded low BF-values up to about 1.3. Higher values (up to the order of 1.5) were found in the middle limb, the yoke and the corners. As a tendency, maximum values were found for outer regions of the laminations. This can be explained by increased distortion of flux density. As a rather unexpected finding, the peripheral corner region yielded very high losses (BF = 1.54). It is a consequence of the very pronounced effective anisotropy of the applied core material, the flux following the rolling direction (RD) like on rails.

Finally, the T-joint region exhibited very high values up to BF = 2 which can be interpreted with the existence of rotational magnetization, *ie* flux turning in the transverse direction (TD) for a part of the period. However, complex flux transfer over the joints yields loss contributions as well.

For a comparison, let us start the discussion of bias with the case of strong DC, Fig. 3(c) considering that very distinct and clear effects are given here. $r_{DC} = 2.7$ yielded a significant general increase of BF throughout the core. Though applied in the middle S-limb, most pronounced effects with loss increases up to the order of 50% are given in the outer T-limb - a "far-off-effect" as earlier also observed with respect to the development of stray fields as a consequence of DC-bias.

The strong increase concerns also the inner parts of the corner. On the other hand side, the increases prove to be distinctly weaker in the other core regions, the typical order being 20%. In special, peripheral parts of the yoke are weakly affected – the peripheral T-joint region showing an increase of as little as 7%.

Comparing Fig. 3(b) with Fig. 3(c) indicates that losses increase with rising r_{DC} in a distinctly non-linear way, corresponding to a tendency of saturation. The ratio of r_{DC} is close to 1:7. On the other hand, the ratio of BF-increases ranges from 1:2 up to about 1:5. It can be concluded that even very weak bias may cause practically relevant increases of *BF* if we consider that capitalization is given for a single percent.

4 DISCUSSION

In very rough approximation, compared to T-joints, limbs show loss increases of doubled intensity. Theoretically, this tendency can be explained by the fact that distinctly changed domain reconstructions are given for alternating magnetization (AM) and rotational magnetization (RM), respectively.

Limbs can be assumed to exhibit pure AM corresponding to well ordered bar domain (BD) structures magnetized in [001], i.e. close to the RD. Mere AC-magnetization will be given through fairly symmetrical displacement of those main Bloch walls which are characterized by high mobility. DC bias yields a shift of working point, corresponding to half-cycle approaching saturation. Typical domain configurations resemble to the image of Fig.4a (which however in fact shows an instant during RM). This is linked with the activation of less mobile walls corresponding to increased hysteresis losses. Classical eddy current (EC) losses will be unchanged since being independent from domains. However, partly annihilation of main Bloch walls yields increased velocity of the remaining ones. This is linked with increased anomalous EC losses. Rises of the two loss portions are reflected by the observed strong increases of *BF*.

T-joints exhibit RM of considerably high axis ratio. The latter is defined as $a = B_{TD}/B_{RD}$ with B_{TD} the induction peak value in TD and B_{RD} that in RD. According to experience, a is up to 0,3 for the given case of GO material. That is, magnetization of 1,7 T in RD is linked with up to 0,5 T in TD. With this rather low value, one part of grains acts as in the case of AM, according to Kerr effect studies (area A in Fig.4b). The rest of material exhibits a more complex behaviour: In instants when ***M*** is close to the RD, magnetization is given through BDs in [001] also here (Fig.4a). But in the rest of the period, a part of the material volume (area B in Fig.4b) exhibits oblique domains (ODs). The latter comprise lancet tubes and plates of merged tubes magnetized in [010] or [100] (plates as arising in similar ways also in the case of mechanical compression [5]).

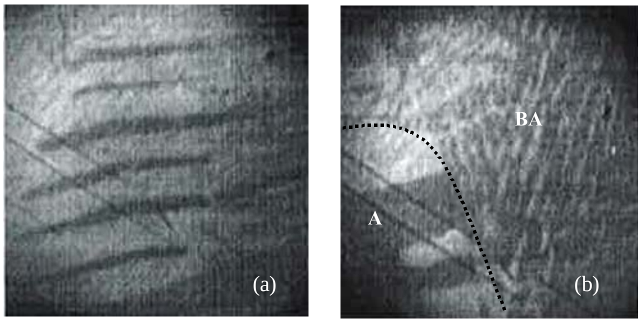

Fig. 4. High-speed Kerr effect domain images [4] for the case of elliptical rotational magnetization. (a) Instant of time when the magnetization vector ***M*** passes through the horizontal rolling direction. Every second bar domain is close to annihilation. (b) Instant when ***M*** is in 60° to the RD, i.e. close to the hard direction. Area A shows bar domains also here. Area B shows narrow surface closure domains which cover inner plate-like domains that are magnetized in oblique directions thus producing ***M*** out of the RD.

Without bias, reconstructions of BDs will yield a basis value of losses which is comparable to AM losses. Generation and reconstruction of ODs yields additional losses which vary between 50% up to more than 100% for a = 0,3, according to the high BF-values of Fig.3a. OD modifications do not involve high wall velocities. Thus the additional losses can be attributed mainly to hysteresis losses.

For T-joints with bias in RD, we can assume that BDs yield loss increases which are comparable to the AC case. On the other hand, reconstructions of ODs will not be affected in substantial ways. That is, both the a priori low anomalous EC losses and the hysteresis losses remain almost unchanged with respect to ODs. In rough approximation, this means that the *absolute* increase of total loss is similar as in the limbs. But the *relative* one is much smaller, in accordance with experimental findings.

5 PRACTICAL RELEVANCE

With respect to the practical relevance of the above, it has to be stressed that the given case of DC-bias is of unbalanced type. AC magnetization was given in all three limbs. But DC magnetization was restricted to the central S-limb. This means that significantly high DC flux is generated, a closed flux path being offered by the outer limbs. In cases (i) and (ii) of Fig.1, this situation will never arise, since DC-bias is distributed to all three limbs. However, in approximation, the above results are valid in those cases which do include closed path for back-flux. For the 3-phase case, this is given with restrictions for the case that the core is arranged in a ferromagnetic tank that acts as a back yoke. Without restrictions, it is given for 5-limb cores where the outer limbs offer back-flux.

In a significant way, the above results are representative for 1-phase cores where a closed path is given in all cases. In future this will show increased significance due to the tendency that very large 3-phase machines are being replaced by three 1-phase machines in increasing ways.

High values of r_{DC} are restricted to GICs (case (i) according to Fig.1). Their duration does not exceed the order of days. Thus even strong increases of *BF* are without energetic relevance. On the other hand side, the cases (ii) and (iii) may arise in permanent ways. The effects tend to be weaker, but they have long-term character. Considering the non-linear increase of *BF* with increasing r_{DC}, a value r_{DC} = 0,01 may yield 1% increase of *BF* as a very rough estimation. In industrial practice, single percent variations of *BF* are capitalized.

Finally it should be mentioned that the increase of losses can be assumed to be linked with an increase of audible noise due to the fact that bias yields increasing magnetostriction through the formation of plate domains.

6 MAIN CONCLUSIONS

By means of the rise-of-temperature method, the local distribution of building factor *BF* was measured at 23 positions in a model transformer core assembled from grain oriented SiFe. In a systematic way, the case of mere AC excitation was compared with that of additional DC magnetization. The results yield the following main conclusions:

(1) For mere AC excitation, lowest *BF* arises in central parts of outer limbs, higher ones in the middle limb and the yokes.
(2) Highest *BF* arises in the corners and – in special – in the T-joint as a result of rotational magnetization (RM).
(3) Unbalanced DC-bias in the S-limb winding yields increased *BF* throughout the core.
(4) Strongest increases arise in limbs where mere alternating magnetization (AM) is given, considerably weaker ones in the T-joints with RM.
(5) Considering domain configurations, strong effects in AM-regions are interpreted with pronounced increases of both hysteresis losses and anomalous eddy current losses.
(6) Weak effects in RM-regions are interpreted with restricted loss increases in those grains which exhibit obliquely magnetized plate-like domains during a part of the period.
(7) As well known, the increase of *BF* is weak for balanced bias in all three limbs of a 3-phase 3-limb core, but it proves to be strongly enhanced in the here investigated unbalanced case, and thus also in the 5-limb case and the 1-phase case.
(8) In the latter cases, 1% bias may yield 1% increase of *BF* as a very rough estimation.
(9) An increase of *BF* can be expected to be linked with an increase of audible noise due to increasing magnetostriction.

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