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Effect of external DC field on current transformers with amorphous and nanocrystalline cores

Pavel Ripka, Mehran Mirzaei, Pavel Mlejnek

[a] *Faculty of Electrical Engineering, Czech Technical University, Technicka 2, 166 27 Prague 6, Czech Republic*

Abstract

Nanocrystalline and amorphous stress-annealed and field annealed tapes are used for cores of DC-tolerant current transformers. We analyze the influence of external DC field of arbitrary direction on the performance of these transformers. For the realistic core shapes the demagnetization is high, which leads to effective external field suppression. However, DC tolerant transformers are tolerant to the DC component of the current and not to the external field - they can be saturated by 30 mT field from permanent magnet. This means that for the practical applications in domestic energy meters some external shielding is required.

Keywords: DC tolerant current transformer, AC current sensor, creep-induced anisotropy, nanocrystalline alloy

I. INTRODUCTION

Nanocrystalline materials are popular for the design of instrument current transformers due to their large saturation induction and linear magnetization characteristics leading to small amplitude error and constant angular error which can be compensated [1]. Another advantage is higher frequency band and lower cost compared to classical NiFe alloys [2]. Besides the basic accuracy, one of the main concerns for practical application of current transformers in electric power meters is their resistance to DC component in the measured current [3] and also on the external DC magnetic field [4].

High values of anisotropy in FeCuNbSiB nanocrystalline alloys can be obtained by stress annealing [5] or field annealing. This treatment results in even more flat hysteresis loops with relative permeability in the range of 10 000 to 500 [6]. These materials usually have strong in-plane anisotropy with easy direction transverse to the ribbon axis; the values of permeability in this direction are rarely published, but we expect that they are much higher than those of isotropic material. It is also known that current transformers are affected by DC field of permanent magnet and they need ferromagnetic shielding [7].

The most popular application of flat-loop nanocrystalline cores is in DC-tolerant current transformers [8]. These transformers are strongly resistant to DC component in the measured current; but is their resistance to external magnetic field compromised by increased axial permeability?

In this paper we analyzed current transformers with amorphous and nanocrystalline cores, both standard (high-permeability] types and DC tolerant types. We measured their response to external DC fields of arbitrary direction: influence of the DC field on differential permeability in circumferential direction and also to the amplitude and phase errors. We also perform FEM modelling to estimate the material properties in transverse direction (axial to the ring). We define directions of the external field in Fig. 1

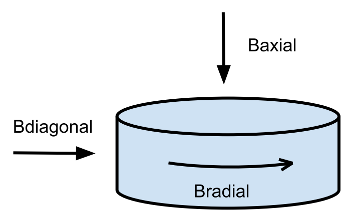


Fig. 1 Definition of the field directions in this paper

II. THE ANALYZED TRANSFORMERS

We have analyzed three 60 A current transformers with similar size 2500 turns secondary winding. The performance of three core material is compared: anisotropic and isotropic cores from nanocrystalline material VITROPERM and anisotropic core from amorphous VITROVAC alloy. All transformers are products of VAC Hanau. The detailed parameters of the transformers are in Table 1.

		DC tolerant		Nontolerant
		nanocrystalline X131	amorphous X501	nanocrystalline VITROPERM X502
Rated primary current	I_1	60 A		
Number of secondary turns	N_2	2 500 turns		

Internal core diameter	D_1	26.6 mm	17	17.3
External core diameter	D_2	21.2 mm	22	22.3
Core height	h	7.2 mm	7	6
Core cross-section	A	19.44 mm^2	17.5	15
Mean flux line length	l_{mean}	75 mm	61.26	62.2
Nominal secondary inductance	L_{nom} (H)	3.8	3	122
Nominal phase error	δφ (°)	3.5	4.06	0.13
Measured secondary inductance	L (H)	4	3	226 @ 1V, 72 Hz 209 @ 0.1V, 72 Hz
Calculated relative circular permeability	**μ_r**	**1 967**	**1 337**	**119 000**

III. THE EFFECT OF DC CURRENT COMPONENT

We have measured small-signal inductance of the secondary windings as a function of DC current component; the measurement was made using LRC meter Hameg HM 8118 (Fig. 2). Using the ring size we calculated incremental permeability and by integration also the amplitude permeability (Fig. 3). As expected, the maximum inductance and corresponding permeability of isotropic (non-tolerant) transformer was very high, but gradually decreasing even for small DC current component. Contrary to that, the characteristics of the DC-tolerant cores is more flat. Decrease of permeability results in increase of the transformer error [9] which we demonstrate on the measured results in Fig. 4.

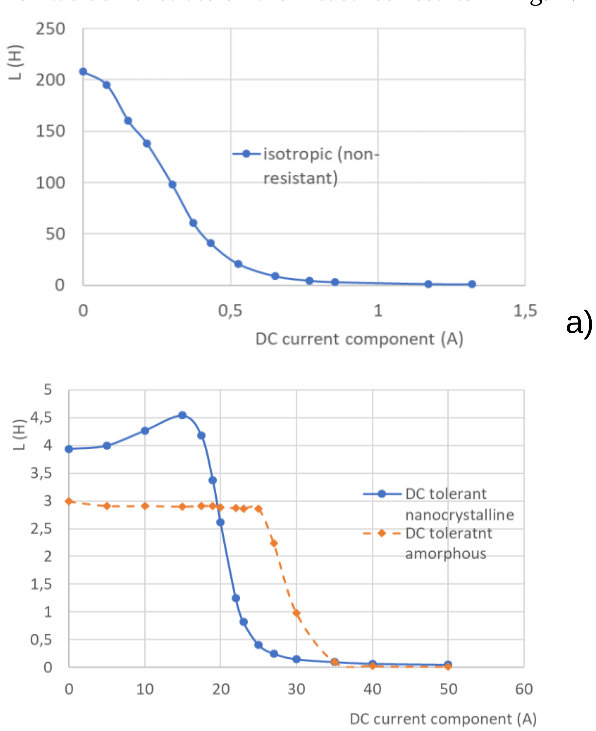


Fig. 2 small-signal inductance as a function of DC current component for a) non-tolerant (high permeability) nanocrystalline transformer b) DC-tolerant transformers

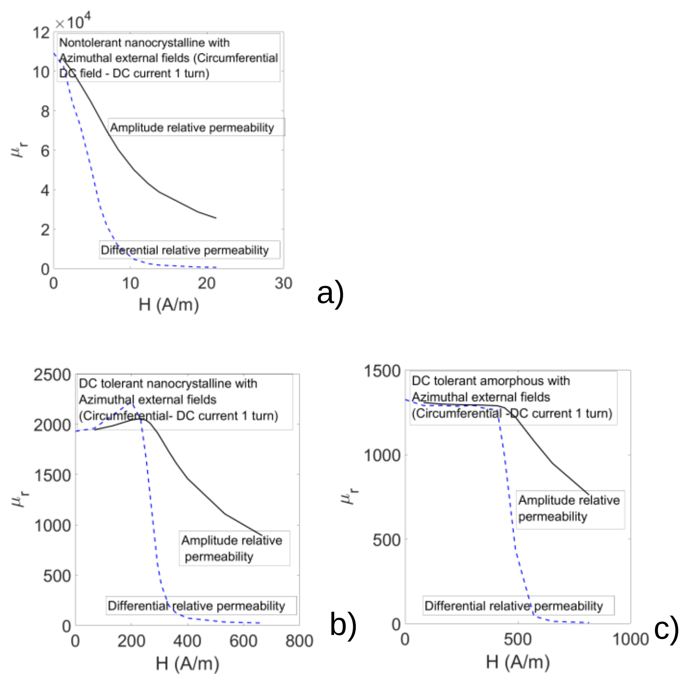


Fig. 3 Incremental and amplitude permeabilities of the measured transformer cores a) non-tolerant (high permeability) nanocrystalline transformer b) DC-tolerant transformers

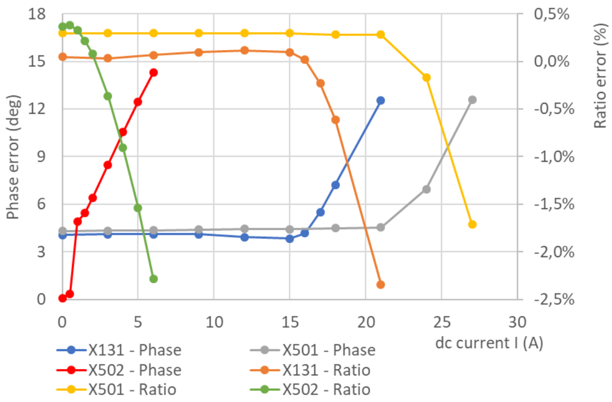


Fig. 4 Transformer errors vs DC current level

IV. THE EFFECT OF AXIAL DC FIELD

When the external field is in axial direction, we should take into the account the demagnetization and also eventual anisotropy. The magnetic field inside the core is no longer homogenous and should be calculated by FEM , as shown in Fig. 5.

b)

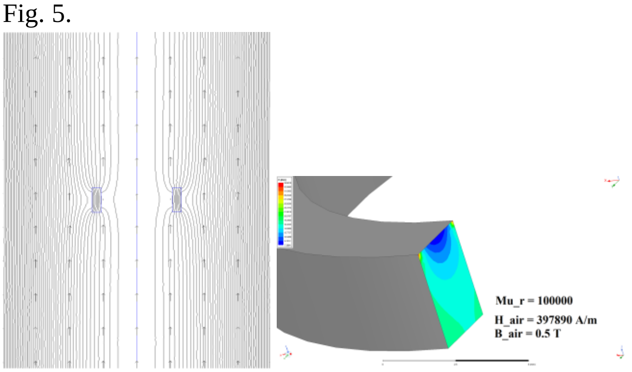
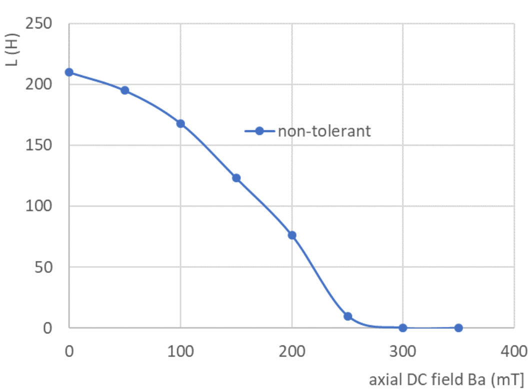
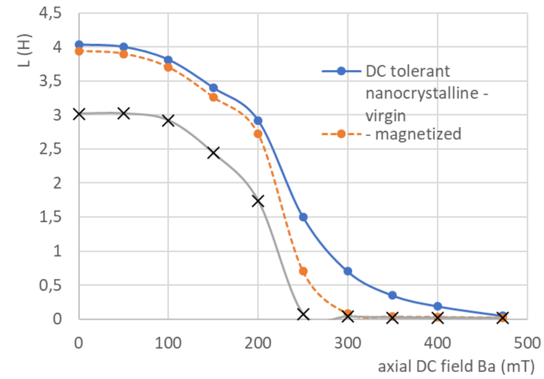


Fig. 5: FEM model of transformer ring core in axial DC field

The measured inductance values (Fig. 6) indicate similar axial field resistance for all measured transformers. This was verified by FEM simulations indicating that apparent permeability of unsaturated rings of these sizes is around 3, and it is practically independent of relative permeability μ_r, if μ_r>1000. Similar are also error curves shown in 7: if the axial field is higher than 200 mT, the error abruptly increases.



a)



b)

Fig. 6 small-signal inductance as a function of DC axial field for a) non-tolerant (high permeability) transformer b) DC-tolerant transformer

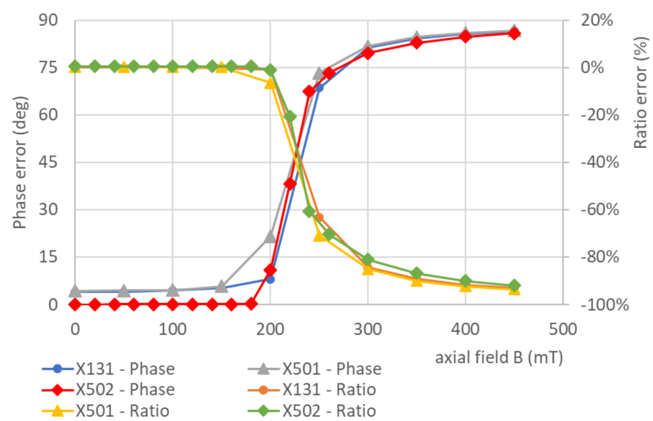
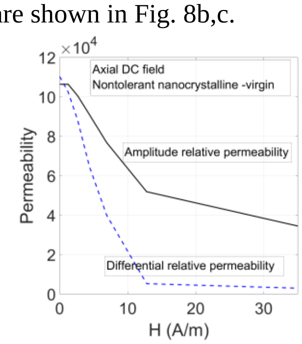


Fig. 7 Transformer errors vs DC axial field

We also reconstructed permeability curves in axial direction (transverse to the tape direction). This was made using by iterative FEM procedure assuming rotational magnetization process. For the isotropic core the obtained curve shown in Fig. 8a fits well with measured curve in circumferential direction (Fig. 2a). For the DC-tolerant cores the reconstructed curves are shown in Fig. 8b,c.



a)

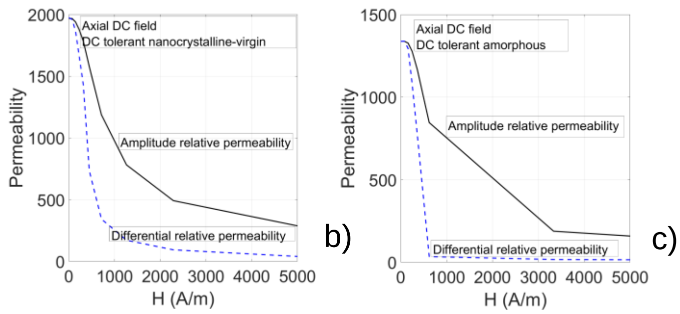


Fig. 8 Permeability in axial direction estimated by iterative FEM

V. THE EFFECT OF DC FIELD IN THE DIAGONAL PLANE

Flux lines distribution and flux density values for the external DC field in the diagonal direction are shown in Fig. 9. The measured inductance values indicate much lower demagnetization compared to axial direction (Fig. 10). This is confirmed in the measured errors, which rapidly grow for field larger than 30 mT as shown in Fig. 11. Fig. 12 shows the calculated permeability values.

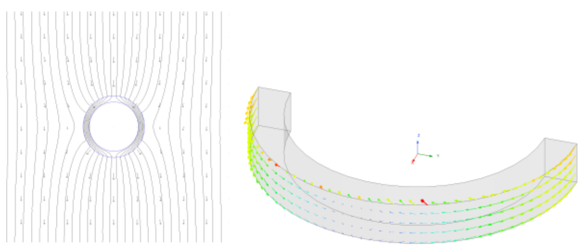
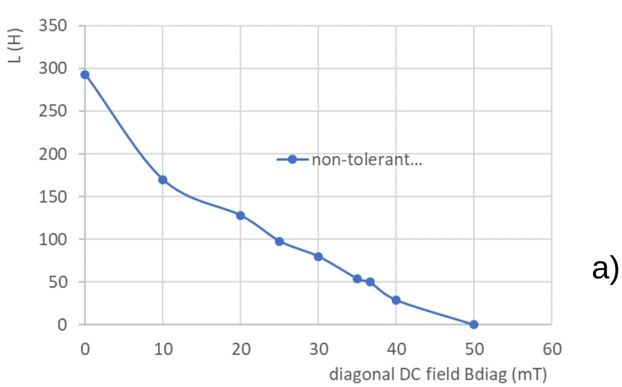


Fig. 9 FEM model of transformer ring core for diagonal (in the plane of ring) DC field



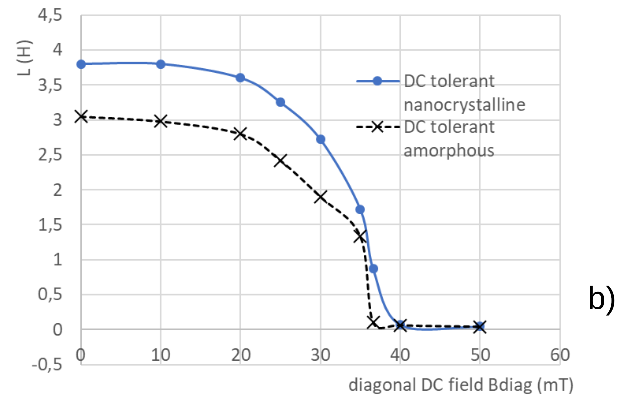
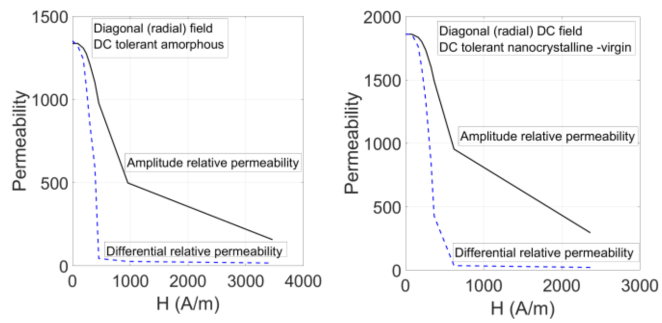


Fig. 10 Small-signal inductance as a function of DC diagonal field



for a) non-tolerant transformer b) DC-tolerant transformers

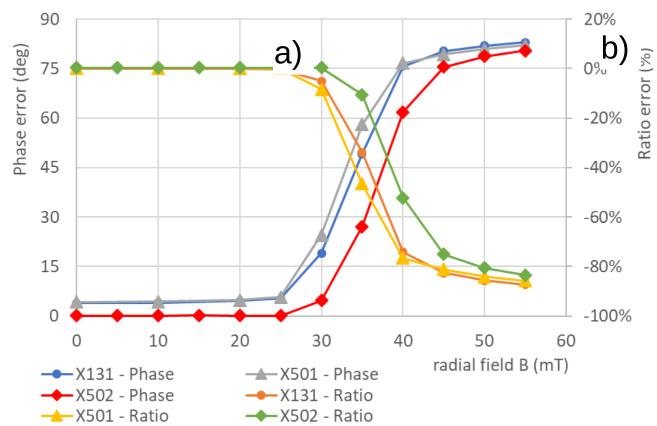


Fig. 11 Transformer errors vs DC diagonal field

Fig. 12 Permeability for diagonal direction estimated by iterative FEM

CONCLUSION

DC resistant transformers with field-annealed core have similar resistance against external DC field as untreated high-permeability isotropic cores. While the ratio error is below 0.2 % for axial field resistance of 200 mT, field of 10 to 50 mT (depending on core material) applied in diagonal (in-plane) direction may easily saturate these cores. This means that additional shielding is necessary to prevent tampering of electricity meters by strong permanent magnet. Using iterative

FEM we were able to estimate diagonal and axial material permeability. We believe that the materials used for the DC-resistant current transformers have relatively low anisotropy, as the calculated material permeability values in circumferential and axial directions are similar. This was confirmed by the information from the manufacturer which indicates that the DC resistant cores were field/annealed rather than stress-annealed.

ACKNOWLEDGMENT

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