3D to 2D Equivalence for a Transverse Flux Reluctance Motor

M. Crivii[1], I.-A. Viorel[2], M. Jufer[1], I. Hussain[3]

[1] Swiss Federal Institute of Technology Lausanne, LEME,
ELG – Ecublens, CH-1015 Lausanne
e-mail: Mircea.Crivii@epfl.ch

[2] Dept. of Electrical Machines, Technical University of Cluj-Napoca
Daicoviciu 15, RO-3400 Cluj-Napoca, Romania
phone: +40 64 195 699 – fax: +40 64 192 055;
e-mail: Ioan.Adrian.Viorel@mae.utcluj.ro

[3] University of Akron, Dept. of Electrical Engineering
Akron, OH 44325-3904, USA
e-mail: ihusain@uakron.edu

***Abstract* —Transverse flux reluctance motor (TFRM) is a relatively new topology of electrical machines. Since the TFRM has a simple construction and assures a high torque per volume ratio its further development is expected. The TFRM has an essential 3D configuration and in the paper a simple equivalence from the 3D pattern to a 2D one is proposed. The obtained results, via 3D and 2D FEM analysis, stand by to prove the usefulness of the equivalence which allows for a 2D FEM characteristics computation of the 3D TFRM pattern.**

1. Introduction

The transverse flux (TF) motor is a relatively new topology of electrical machines, its configuration being first proposed by Weh in the '80s [1]. The TF motor has a topology with a torroidal armature coil, where the current flows parallel to the direction of rotation. The stator core is essentially salient, with a great number of poles. The homopolar type MMF produced by the current, which flows through the stator coil, is modulated by the stator pole pattern to a heteropolar air-gap flux. The rotor can be built up with salient poles, that is the case of the TF reluctance machine, or with permanent magnets (PM) in different topologies, as surface mounted PMs or inserted in the rotor core PMs.

The TF reluctance motor (TFRM) without PMs or coils on the rotor, has a topology pretty closed to that of the switched reluctance machine (SRM). There are two important differences between TF reluctance motor and SRM [2]:

- The TFRM's stator winding has one torroidal coil for each phase; the machine is essentially a homopolar one. The SRM has an independent excitation coil for each stator pole and is a heteropolar machine.
- The TFRM has the same number of poles on the stator and rotor while in the case of SRM it is different.

The TFRM has a 3D configuration due to its homopolar excitation, even the fluxes are not transversal in stator or rotor. The SRM can be reduced to a 2D cross-section if its axial length is large enough.

Until now were proposed some variants of TFRM, for instance [2], [3]. It is expected a further development in the field since the TFRM has a simple construction and assures a higher torque per volume compared with SRM or with classical machines. The design of the TFRM, a proposal is discussed in [4], must relay on the magnetic field analysis, and TFRM has an essential 3D configuration. The attempt to solve the 3D configuration specific for TFRM by transforming it in two 2D configurations made in [3], [4] was quite satisfactory, even the equivalence is not entirely defined.

In the paper a simple equivalence from a 3D pattern to a 2D configuration is proposed. The equivalence is based on the fact that the TFRM has quite the same structure as a SRM. It is shown in the paper that if only one pole of a TFRM phase is considered the equivalence to one pole of a corresponding SRM is quite good. Therefore the TFRM characteristics, as static torque function of rotor position can be obtained as a result of a 2D magnetic field analysis done for the equivalent SRM. The details concerning the equivalence, the imposed conditions and the shortcomings are presented in the paper. To sustain the proposal a comparison between the results obtained by magnetic field analysis on the 3D configuration and on the proposed 2D equivalence is made.

The proposed equivalence is an acceptable one, the errors being caused mainly by the leakage flux, which differs between the 3D configuration and the 2D structure.

The proposed method is fairly useful in designing stage of a TFRM, allowing for quite easy and fast static and dynamic characteristic computation.

2. The equivalence between TFRM and SRM

The discussed TFRM has quite an uncomplicated, classical, structure, Fig.1, where is shown only a phase of a six poles machine.

It is a single-sided motor with exterior stator and interior rotor. The stator has a torroidal phase winding which carries circumferential current. Each phase winding is surrounded by equidistant ferromagnetic salient poles fixed in a nonmagnetic case not shown in the figure.

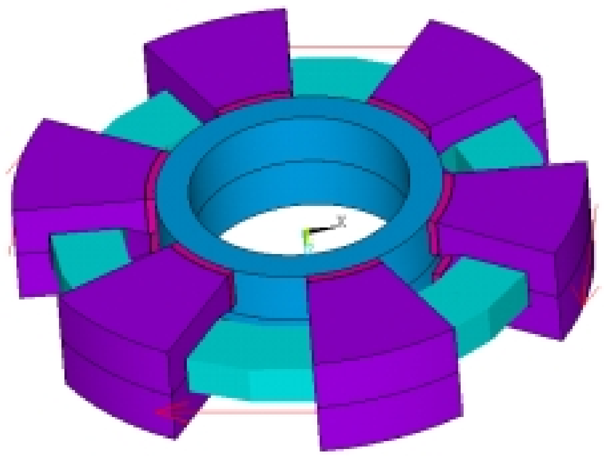

Fig. 1. Six pole TFRM, one phase, poles in aligned position

The rotor has no winding, but equidistant salient ferromagnetic poles placed on a rotor nonmagnetic, or magnetic, carrier. Both, the stator and rotor, poles can be built up of conventional magnetic sheets disposed axially, or of soft magnetic material. Since there are not entirely 3D flux paths the soft magnetic material may be only an option. The rotor has the same number of poles like the stator, the poles' width being equal for the stator and for the rotor.

When a current flows through a stator phase winding, the rotor will move to a position where its poles will be aligned to the stator poles, Fig.1. The aligned position is an equilibrium one and with only one phase the rotor should remain in this position. In order to obtain a continuous movement the motor must have at least three phases placed axially, side by side, on the motor shaft.

There are two possibilities to obtain the phases displacement; to keep aligned axially the stator poles and to shift from phase to phase the rotor poles, or viceversa. There are also different possible topologies, not only the one presented in Fig.1, but as far as the equivalence discussed in the paper is concerned, these aspects are quite unrelevant.

It must be mentioned only the fact that the larger number of phases leads to the smoother steady state torque. Since the TFRM behaves and is fed like a reluctance synchronous motor, the supply and control system should be based on the electronic converters which exist on the market. It means that the three phases TFRM structure is the most suitable.

The usual topology of a TFRM is quite similar, for one phase, with the SRM one, but the last has different number of poles on the stator and on the rotor. The way the torque is developed is the same, too. Considering one pole from these two machines the structure is different only due to the difference which exists in the excitation winding. TFRM's phase winding is formed of one torroidal coil carrying circumferential current, since the SRM has an independent coil placed on each pole and a phase is obtained by connecting usually two poles placed in opposition.

The design procedure for these two motors is quite the same, [2]-[5]. The estimation procedure, [2], [5], [6], based on the sizing equation, a simplified magnetic equivalent circuit and on the existing experience, allows to calculate the main dimensions, parameters and performances. The magnetic iron core optimisation and the steady-state characteristics computation should be done via FEM analysis. The difference consists in the fact that in the case of the SRM the 2D-FEM analysis gives quite accurate results, [7], and in the case of the TFRM a 3D-FEM analysis is necessary.

The main condition imposed for the equivalent SRM is to produce the same aligned flux density in the air-gap under the stator pole with quite the same MMF per pole. Since the torque depends on the air-gap flux density variation the air-gap topology must be the same too.

The equivalent SRM's stack length is equal to the active TFRM stator pole length and, consequently, smaller than the TFRM rotor length per phase. The equivalent SRM will have the same number of poles on the stator and rotor, as in Fig. 12, and its geometry is quite unusual, the stator slot area being double of the TFRM's slot area. Since the equivalent SRM will not be built up its dimensions are not that important. The equivalent SRM should have the same yoke cross-section as the TRFM, both in the stator and in the rotor.

If the equivalent SRM can not be obtained, due to the imposed dimensions, than a scaling procedure [2] should be applied both to TFRM and corresponding SRM. Nobody should cares about SRM heating and cooling, therefore a higher current density can be adopted in order to fit the necessary ampere turns into a smaller slot area.

Different TFRMs' and corresponding SRMs' were considered, the lowest number of poles being 6 as in Fig. 1. In all the cases the equivalence was good. Only the results for a 28 poles per phase configurations are given in the paper since it is a typical example with quite an adequate number of poles.

3. Computed results and conclusion

The TFRM has 28 poles per phase and exterior stator. Fig. 2 shows two poles from the stator and rotor in aligned position and the phase coil with the flowing current direction.

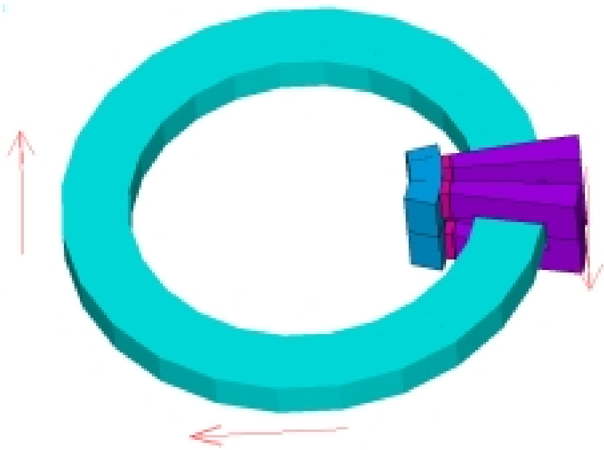

Fig. 2. Two poles and the excitation coil of one phase, 28 poles TFRM

The TFRM dimensions were computed via a designing estimation procedure [2]. The cross-section through motor's stator and rotor poles is shown in Fig. 3.

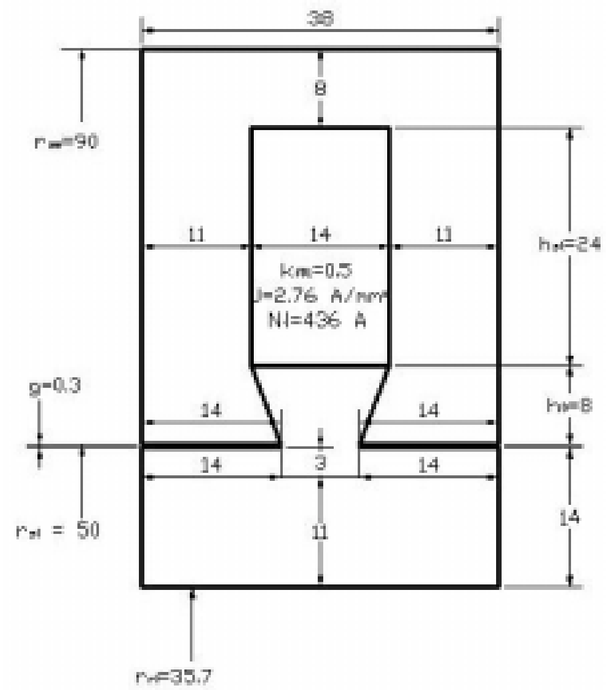

Fig. 3. TFRM main dimensions

The 3D computed flux density for aligned and unaligned position of TFRM, only two poles shown, is given in Figs. 4 and 5 respectively.

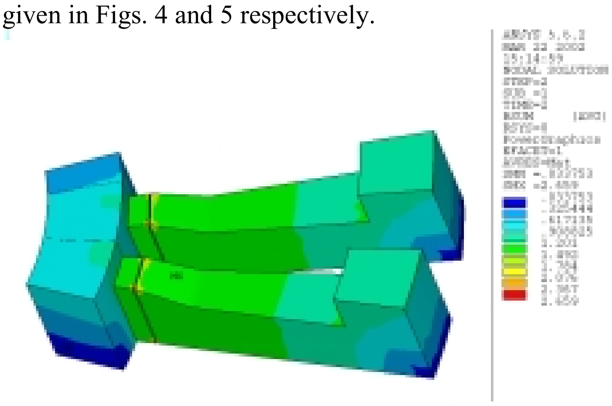
Fig. 4. TFRM 3D flux density, aligned position, 463 A/phase total current

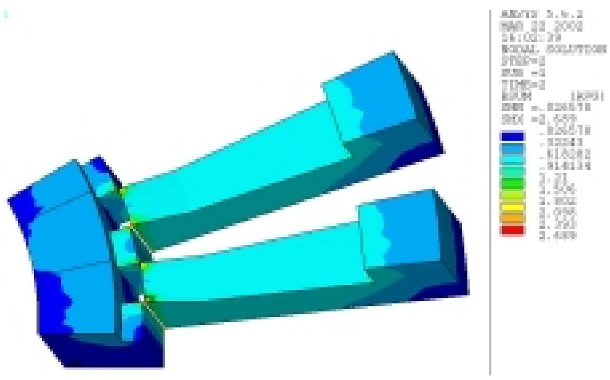
Fig. 5. TFRM 3D flux density, unaligned position, 463 A/phase total current

The air-gap flux density, in the stator poles axes on the circumferential direction, computed via 3D FEM for aligned position is given in Fig. 6.

The air-gap flux density in the stator pole axis on the axial direction, computed via 3D FEM for aligned position is given in Fig. 7.

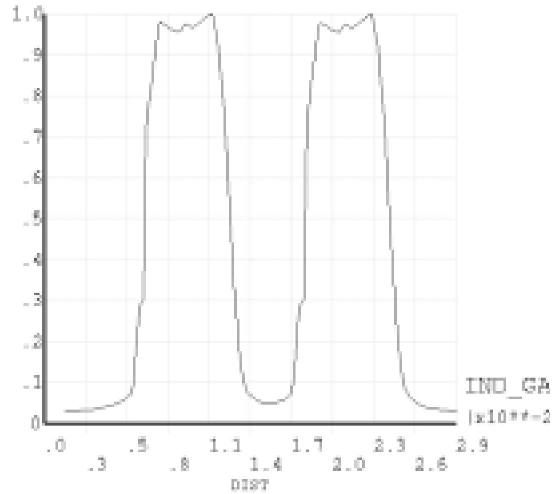

Fig. 6. Air-gap flux density variation in circumferential direction, 3D FEM, aligned position, 463 A

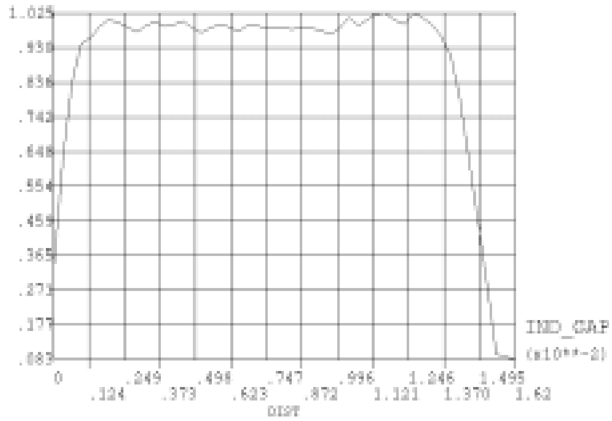

Fig. 7. Air-gap flux density variation in axial direction, 3D FEM, aligned position

The air-gap flux density under the pole in aligned position is quite constant, its value being around 1T. The computed value of the maximum air-gap flux density is:

$$B_{gM} = \frac{N \cdot i \cdot \mu_0}{2g} = \frac{4\pi \cdot 10^{-7} \cdot 463}{6 \cdot 10^{-4}} = 0.969 \text{ T} \qquad (1)$$

and the correspondence is very good, since the machine is not saturated.

The torque variation versus rotor position is given in Fig. 8, the per pole average value being T_{av}=0.3033 Nm. The average torque per phase is T=8.4924 Nm. Analytically computed torque per phase is:

$$T = Q_S \cdot \frac{1}{2} \cdot N \cdot i \cdot A_p \cdot \frac{B_{gM}}{\Delta\theta}$$

$$T = 14 \cdot 463 \cdot 0.028 \cdot 0.0056 \cdot \frac{0.969}{\pi} \cdot 28 = 8.782 \text{ Nm}$$

The notations are:

- Stator number of poles, Q_s=28
- Total current, $N \cdot i$=463 A
- Stator pole area, A_p=0.028·0.0056 m^2
- Maximum air-gap flux density, B_{gM}=0.969 T
- Angular stroke pitch, $\Delta\theta$=π/28 rad

Fig. 8. Torque variation versus rotor position, 28 poles TFRM, 3D FEM, 463 A

The TFRM 2D FEM analysis was done for one half of a stator and rotor tooth in aligned position, Fig. 9, the flux density map in the poles axial section being given in Fig. 10. The air-gap flux density variation in the axial direction is given in Fig. 11, the values being quite the same as the ones given in Fig. 7 and computed via 3D FEM.

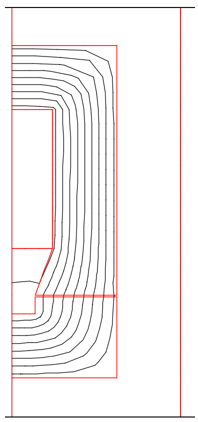

Fig. 9. Flux plot, aligned position, TFRM 2D FEM analysis, 436 A

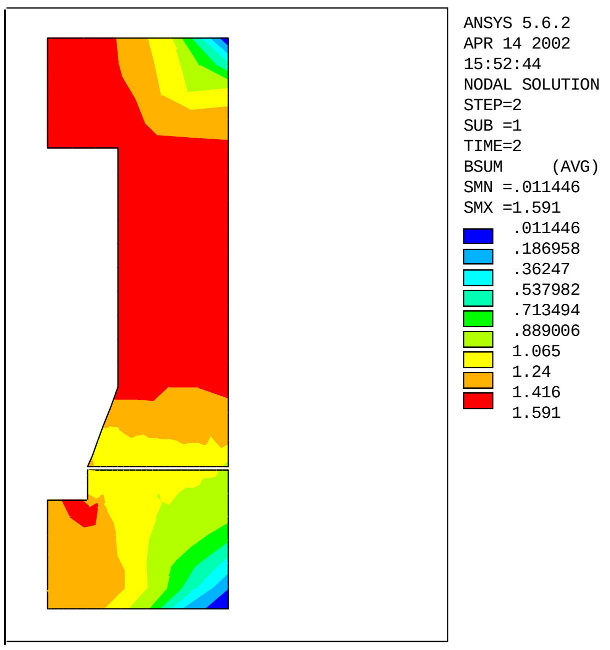

Fig. 10. Flux density map, aligned position, TFRM, 2D FEM analysis, 463 A.

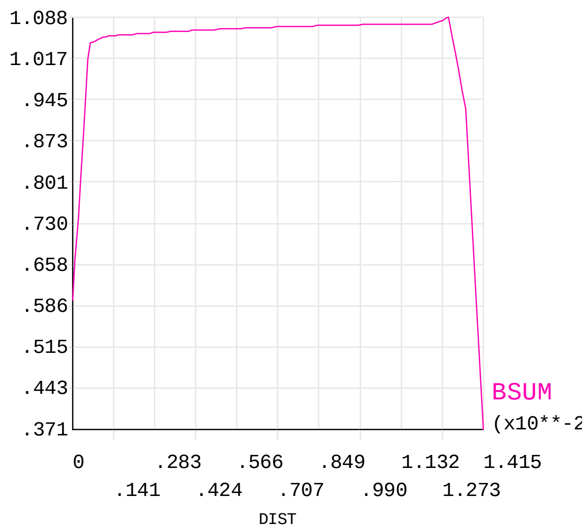

Fig. 11. Air-gap flux density on the axial direction, TFRM 2D FEM analysis, 463 A

The equivalent SRM has 28 poles, both on the stator and rotor, the flux plot for the entirely motor cross-section, only one pole coil supplied, is given in Fig. 12.

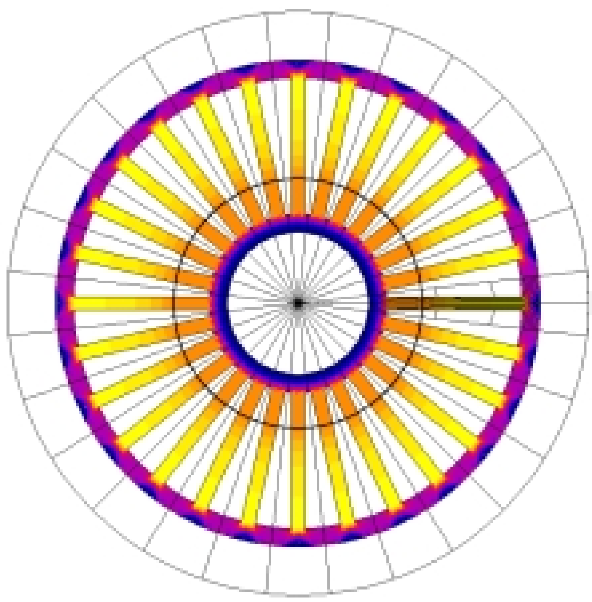

Fig. 12. Flux plot, equivalent SRM cross-section, one pole's coil supplied, 463 A

The flux plot and the flux density map for aligned position of equivalent SRM are given in Figs 13 and 14 respectively.

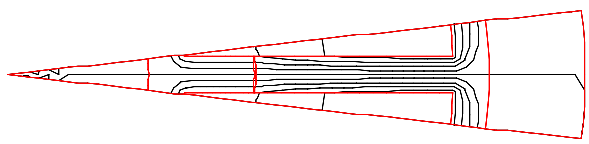

Fig. 13. Flux plot, equivalent SRM, aligned position, 463 A

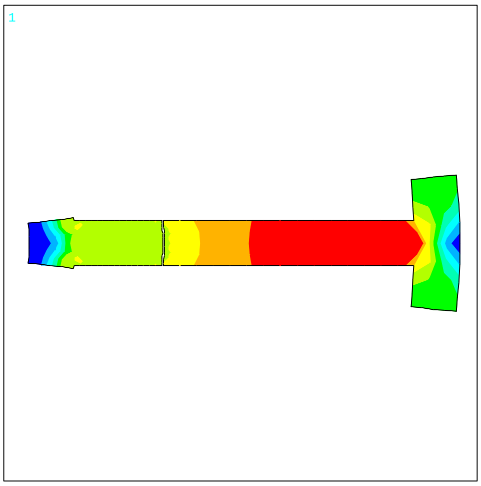

Fig. 14. Flux density map, equivalent SRM, aligned position, 463 A

The air-gap flux density variation under the equivalent SRM stator pole in aligned position is given in Fig. 15.

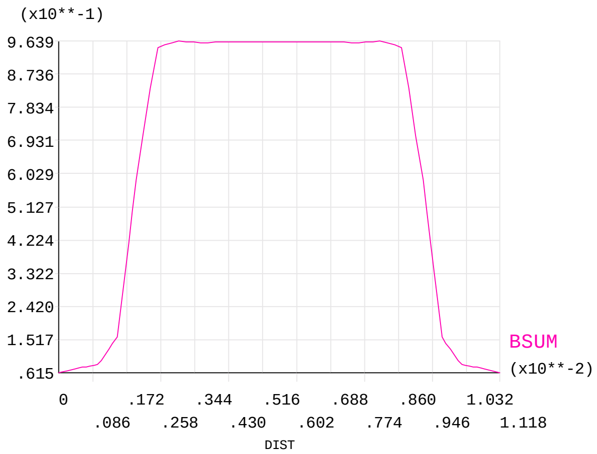

Fig. 15. The air-gap flux density variation under the equivalent SRM stator pole in aligned position

The values are smaller than the ones obtained for the TFRM in the axial direction via 2D FEM, Fig. 11, or via 3D FEM, Fig. 7, and so is the average torque per pole, $T_{av}^{*} = 0.297$ Nm . The torque per pole variation of the equivalent SRM, function of the rotor position is shown in Fig. 16, only one coil being fed with total current of 463 A.

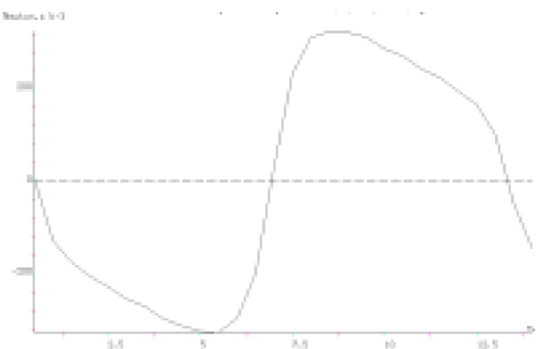

Fig. 16. Air-gap flux density, equivalent SRM, aligned position, circumferential direction, 463 A

The differences which exist between the TFRM and its equivalent SRM concerning the air-gap flux density value and the torque has two main causes.

First, in the case of the equivalent SRM the magnetising flux path is longer than it is in the TFRM. Therefore the MMF drop in the core is larger in the equivalent SRM and consequently it resulted a smaller value for the air-gap flux density. This difference can be eliminated increasing slightly the pole total current in the equivalent SRM. The pole total current of the equivalent SRM must be obtained via 2D FEM analysis, Figs 13, 14 and 15. The increased current should assure the same air-gap flux density as in the 2D FEM analysis done on TFRM, Figs 9, 10 and 11.

Second, in the case of TFRM 3D FEM analysis the important leakage flux can be a cause of a quite unusual torque variation. As one can see from Fig. 6 in an unaligned position the value of the air-gap flux density is almost 10 % of the maximum value obtained in aligned position, larger than in the equivalent SRM case, Fig. 15. The symmetry conditions imposed in the case of TFRM 3D FEM analysis play a role in modifying the torque since for the six poles 3D FEM analysis, where were no symmetry conditions, the torque looks different, Fig. 17.

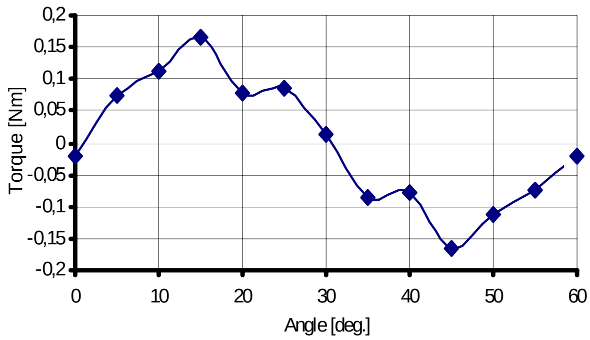

Fig. 17. Torque versus rotor position, 6 pole TFRM, 3D FEM analysis, 150 A

Considering all the obtained results the conclusion is that the proposed 3D to 2D equivalence for TFRM is a valuable tool and can be applied in the design/estimation procedure stage. The equivalent SRM should have:

- The same value of the flux density in the air-gap in aligned position as the TFRM
- The same number of poles
- The same topology in the air-gap, which means the same air-gap diameter, polar pitch, pole width and stack length.

First the 2D FEM analysis will be applied to the TFRM, the plane being considered on the axial direction, as in Figs 9, 10 and 11.

It follows the 2D FEM analysis done taking into account the imposed conditions given above.

Than, once found the adequate total current for the equivalent SRM, the steady state and transient characteristics can be computed by 2D FEM analysis applied on that motor.

The leakage inductances are different and one must consider it in computing the parameters.

The proposed equivalence is a simple one and can be a useful tool for designers or researchers working in this field. Such an equivalence can be extended to other variable reluctance machines with adequate changes.

Aknowledgments

The work was possible due to the support given by EPFL, Romanian Ministry of Education and Science and NSF to the authors.

References

[1] H. Weh, J. Jiang, "Berechnungsgrundlagen fur Transversalflussmaschinen", *A f. E*, Vol. 71, pp. 187-198, 1998.

[2] G. Henneberger, I.A. Viorel, *Variable reluctance electrical machines*, Shaker Verlag, Aachen (2001).

[3] R. Kruse, G. Pfaff, C. Pfeiffer, H-L. Wehner, E. Hopper, "New concept of a low-speed direct servo drive", in: *Proc. of PCIM '98*, Vol. Intelligent Motion, pp. 1-10.

[4] R. Kruse, "Calculation method for a transverse flux reluctance motor", in: *Proc. of OPTIM' 2000*, pp. 387-392.

[5] R. Blissenbach, I.A. Viorel, G. Henneberger, "On the single-sided transverse flux machine design", *EMPS*, Vol. 30 (2003)

[6] S. Huang, J. Luo, T.A. Lipo, "Evaluation of the transverse flux circumferential current machine by use of sizing equations", in: *Proc. of IEEE-IEMDC 1997*, pp. WB.2-15.1-WB.2-15.3 (1997)

[7] A. Brösse, *Sensorloser Betrieb eines geschalteten Reluktanzmotors mittels Kalman Filter*, Dissertation Thesis, Institut für Elektrische Maschinen der RTWH, Aachen (1998)