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SINGLE-SIDED TRANSVERSE FLUX MOTORS

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Abstract. The transverse flux (TF) machine represents one of the newest topologies of electrical machines. The homopolar MMF in a TF machine, produced by a phase winding of toroidal form that carries current in the circumferential direction, is modulated by the stator poles to produce a heteropolar flux density distribution in the air-gap. The homopolar features of TF machines allow them to achieve more mechanical force with less armature current, thus the machine has higher torque both with respect to volume and to weight than any conventional motor. The complicated construction of the TF machine, with a true 3D flux path pattern, is fully compensated by its good performance. Thus the TF machine is very well suited for direct variable speed drive systems. The paper presents the single-sided TF motor, with strength on the machine mathematical model, construction and design. The comprehensive presentation covers the main aspects of the single-sided TF motor, offering a guideline for the user or designer of such a motor.

Keywords: Electrical machines, Transverse flux topology, Modeling, Design.

1. INTRODUCTION

The transverse flux (TF) machine is a relatively new topology of electrical machines. The TF machine was first proposed and named by Weh [1] in the late ‘80s. By now, there have been reports on several variants of TF machines [2-8], which have the same basic principle. A stator phase winding of toroidal form carries current in the circumferential direction. The homopolar MMF produced is modulated by the stator poles, or teeth, to produce a heteroplar flux density distribution in the air-gap. The stator core is essentially salient with a great number of poles. The rotor is usually built up with permanent magnets, but it can also be constructed only with salient poles, when the machine is a reluctant one.

The homoplar features of TF machines allow them to avoid the limitation of the well known “BiL” principle of force production. Thus the MMF distribution with one pole pattern, modulated by the toothed structure to produce an air-gap MMF with a different pole pattern, offers the possibility to achieve more mechanical force with less armature current. This means that, at a given machine diameter and armature winding current, the current loading is increased simply by enlarging the number of pole pairs. This effect is used by the TF machine to obtain high specific torque.

The TF machine may have a single-sided or a double-sided stator structure. In both cases, the rotor can be built up with surface mounted permanent magnets (flat magnets rotor), Fig. 1., or with permanent magnets inserted in between the flux concentrating poles (concentrating flux rotor), Fig. 2. In the case of the flat permanent magnets, Fig. 1., besides the U-shaped cores that link the armature winding, there are return I-shaped cores on both stators.

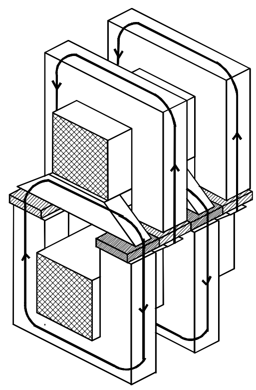

Fig. 1. Double-sided TF machine topology with flat permanent magnets

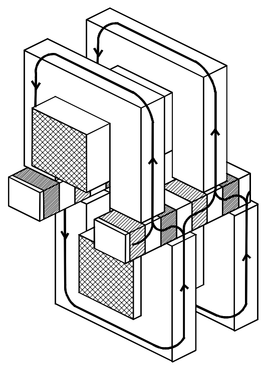

Fig. 2. Double-sided TF machine topology with concentrating flux rotor

For a better view, only a part of a phase in linear arrangement is shown in Figs. 1. and 2, and also in the most explanatory figures in this paper.

A double-sided disk-type TF machine, named "axial-flux modular permanent magnet generator" is reported in [7]. The disk type rotor is of the flux concentrating type. The double sided stator, with two parts shifted half a pole pitch, has two toroidal coils and nine U-shaped cores on each side. Thus the rotor has 18 poles attached to a nonmagnetic disk that holds the rotor cores. A nonmagnetic stainless steel belt is strapped around the rotor. The reported [7] test data show that the disk type double-sided TF machine has a rated output power of 650 W at a rated current of 11 A, rated voltage of 58 V, and a rated rotor speed of 667 rpm. The reported efficiency is about 75% and it can be increased [7] by reducing the core and friction mechanical losses. The disk type variant of the double-sided TF machine implies quite the same shortcomings as the conventional cylindrical variants presented above.

The TF machine topology with double-sided stator, even if it seems to be more promising than the single-sided topologies as far as performance is concerned, implies an important increase in the machine overall dimensions and a complicated construction. Therefore, most prototypes built up or reported under construction at present are of the single-sided topology. From all possible variants, two single-sided stator topologies have been most studied, one with flat magnets rotor and I-shaped return cores on the stator, Fig. 3., and another one with concentrating flux rotor and U-shaped shifted stator poles with pole shoes, Fig. 4. From the three prototypes designed at the Institute of Electrical Machines (IEM), RWTH Aachen, two are of the first type and one of the second type. One of these prototypes, the first one to be designed and built up [2,11] with flat permanent magnets, will be referred to as TF-SM1 in this paper. For this sample machine (SM) the results obtained from 3D-FEM analysis are available, and also the measurements on the test bench and all its geometrical dimensions. (Most of them are given in Appendix 1.)

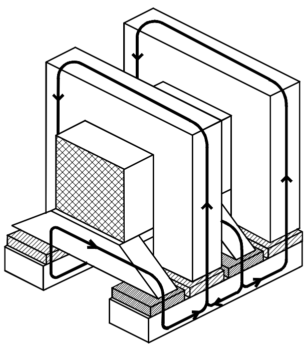

Fig. 3. Single-sided TF machine with flat permanent magnets

The TF machine exhibits a true 3D flux distribution, the main flux path of the TF machine with flat permanent magnets being shown in Fig. 3. The saturation effect is quite important, the permanent magnets change their operating point due to the armature reaction and the variable air-gap reluctance, and the leakage fluxes have greater values than in the conventional machines. All these specific features make the TF machine quite different from the conventional machines as far as the mathematical model and the designing procedure are concerned.

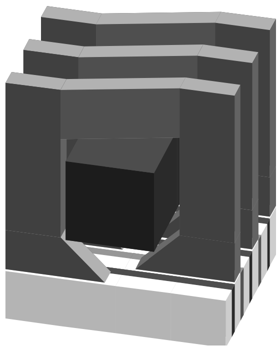

Fig. 4. Single-sided TF machine with concentrating flux rotor

The aim of this paper is to present the single-sided TF machine's specific aspects, with strength on the mathematical model, designing procedure and construction features, having the existing results reported in the referred papers and the experience accumulated in this domain at the Department of Electrical Machines, RWTH Aachen, as background.

2. MATHEMATICAL MODEL

Since the TF machine fundamentally exhibits a 3D magnetic flux pattern with important nonlinearities due to the iron core saturation and permanent magnet operating point change, the conventional circuit type mathematical model cannot be taken into consideration. Two alternatives should be considered, both of them being based on the circuit-field type mathematical model. The difference between these two alternatives lies in the way the field part of the mathematical model is solved, by using a numerical method, usually the finite element method (FEM), or by building up a magnetic equivalent circuit (MEC).

Due to the complex topology of the TF machine, a pertinent MEC is quite difficult to be developed, even if some attempts have been made in this direction [1]. There are three main objectives to be fulfilled by a MEC:

- Taking into account the air-gap variable magnetic reluctance, which changes with the rotor position.
- Computing the magnetic reluctances corresponding to the leakage flux paths.
- Considering the magnetic circuit nonlinearities, which consist of iron core saturation and permanent magnets operating point changes due to the armature reaction and the magnetic reluctance variation.

It is obvious that covering all these objectives correctly is quite impossible, and even if it were possible, the complexity of such a MEC and its computing program will almost be comparable to 3D-FEM analysis, but with poorer results. Once the MEC limits are known, an adequate choice must be made between these two options.

The first option considers a simplified MEC in which the air-gap magnetic reluctance variation and, up to a certain accuracy, the leakage fluxes, or at least the most important of them, are taken into account as much as possible. This option can be used in connection with the sizing equation, [9], and it may be a basis for the first design draft of a single-sided transverse flux machine.

The second option should be considered when a transient behaviour has to be determined, and it has almost nothing in common with the MEC. A MEC can be developed in this case also, by fully using the previously obtained results from a 3D-FEM analysis. As a result of 3D-FEM analysis, the phase flux linkages or the air-gap flux density variation, function of rotor position and armature currents, is computed and the machine transients can be obtained using the following equations:

$$v = R \cdot i + \frac{\partial \lambda}{\partial t} \quad (1)$$

$$\lambda = f(i, \theta) \quad (2)$$

$$\theta = \int \omega \cdot dt \quad (3)$$

$$T = \frac{J}{p} \cdot \frac{d\omega}{dt} + T_l \quad (4)$$

$$T = p \cdot i \cdot \frac{\partial \lambda}{\partial \theta} \quad (5)$$

where v, i, R and λ are the phase terminal voltage, current, resistance and flux linkage respectively, θ is the rotor angular position in electrical radians, ω is the electrical angular frequency and T, T_l are the output and respectively load torque.

Since the simplified MEC, the sizing equation and other related formulae are only used for a first estimation in the TF machine design procedure, FEM analysis remains the essential way to design and steady-state or transient characteristics computation. There have been attempts to model the single-sided TF machine with a 2D-FEM model, [10]. An equivalent 2D model can be found for a single pole pair when the U-shaped core and the armature winding are shifted 90^0 around their vertical axis, Fig. 3. Hence the flux path is moved from the 3D space into the 2D plane and the current density is perpendicular to the 2D plane. This simplification leads to the conventional DC brushless machine model with U-shaped poles core. It is quite obvious that, by introducing this equivalent heteroplar machine, the specific phenomena of the TF machine are not entirely taken into account and the results are unsatisfactory. Things are quite different in the case of the disk type TF machine [7], when the machine topology is favourable to simplified 2D-FEM analysis.

The true field model of a TF machine, with its complicated topology, must be a 3D one. Such models were developed and solved using FEM by almost all researchers involved in this field, some details being reported in [2,3,4,5,6,10,11].

For the TF-SM1, the 3D-FEM computations were carried out using the MagNet programming package, which has a solver able to compute forces in any direction, but the mesh produced is not completely isotropic [10,11].

At first, a 2D mesh with arbitrary geometry was generated, and then it was extruded into the third dimension. The plane of the U-shaped core had to be taken as the base plane for TF-SM1, Fig. 5., the boundary planes between different materials being parallel to the base plane. Since half of the angular pole pitch is only 4.5^0, the model was considered a linear motor model. The 3D mesh contains all the TF machine components for a pole pitch and a half of the axial length of one phase, due to the machine's symmetrical topology in the case of the TF-SM1, Fig. 6.

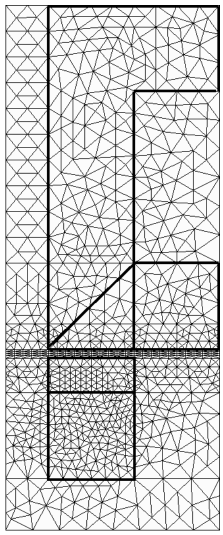

Fig. 5. The base plane for the TF-SM1 model

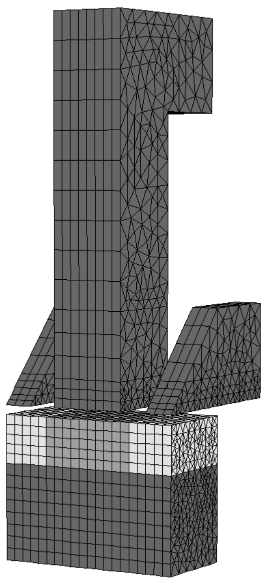

Fig. 6. The TF-SM1 3D mesh of one pole pitch, elements in the air regions being suppressed

The forces were computed using Maxwell's tensor. Since Maxwell's tensor computation procedure is sensitive to the tangential component of the magnetic field , which is small compared to the modulus, the air-gap of the TF-SM1 machine was divided into four layers of elements to increase the precision of the numerical solution. A zoom of the 2D mesh for the air-gap and its neighbourhood is shown in Fig. 7.

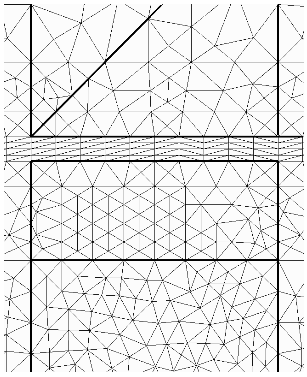

Fig. 7. A zoom of the 2D mesh for the air-gap region

For the TF-SM1 [10,11], the magnetic field was computed considering ten rotor positions and three values of the armature current. Due to the rotor permanent magnets' symmetry, the rotor movement was obtained simply by shifting the permanent magnet material label in the rotor, the mesh remaining the same. The material label was changed with the spatial step of the mesh, Fig. 6. From the 3D-FEM analysis results, different characteristics were obtained for the TF-SM1, such as the stator pole flux variation at no-load, Fig. 8., and elementary phase induced EMF at no-load, Fig. 9. It can be seen that both the flux and the EMF vary quite sinusoidally at no-load. The load current is influencing the flux variation, as shown in Fig. 10., where the flux linkage characteristics versus rotor position with the armature current as parameter are given for the motor reported in [4]. The flux linkage characteristics can be used to fully describe the steady-state or transient behaviour of the TF motor.

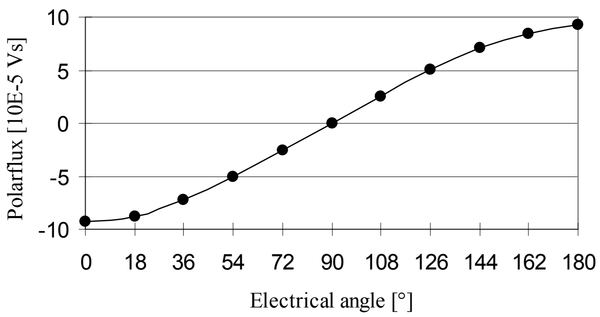

Fig. 8. TF-SM1 pole flux variation versus rotor position at no-load

3. DESIGNING PROCEDURE

The single-sided TF motor exhibits a true 3D flux distribution and it has a quite complicated topology. Taking into account all the specific aspects concerning the single-sided TF motor, its designing procedure cannot be conducted as in the conventional machine's case. The single-sided TF machine electromagnetic designing procedure must consist of the following two parts:

- The main dimensions, parameters and performance estimation, based on the sizing equation, a simplified MEC and some adequate formulae which take into account the existing experience.
- The magnetic circuit optimization and the steady-state and dynamic characteristics computation using 3D-FEM analysis.

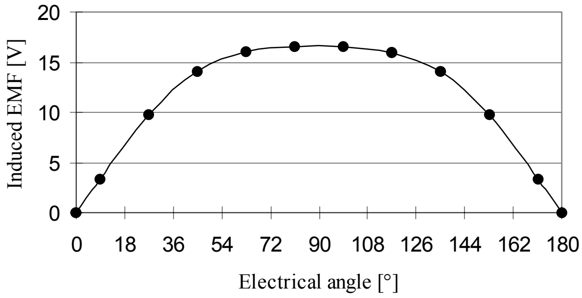

Fig. 9. Elementary phase induced EMF at no-load for TF-SM1

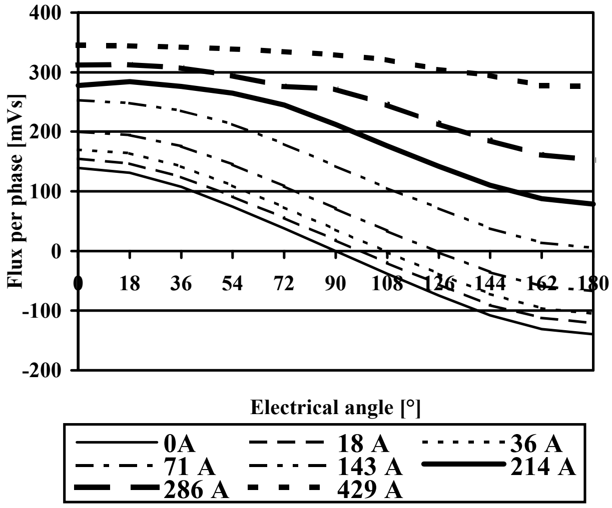

Fig. 10. Phase flux linkage variation versus rotor position with the armature current as parameter for a TF motor with flat permanent magnets rotor

The final TF machine dimensions are obtained after the 3D-FEM analysis, but the estimation procedure is also necessary, since it gives the main entrance values for the second step and reduces the 3D-FEM computations volume. Since the versatility of the 3D-FEM analysis is well known and the model of a single-sided TF machine was discussed in the previous chapter, this chapter will present the design-estimation procedure and some aspects concerning the machine construction.

The single-sided TF motor must have two or more than two phases in order to avoid the start-up difficulties and to obtain a continuous rotation. Since the TF motor must be supplied from an inverter, the three phase solution must be the best possible one, three-phase converters being available on the market. The input phase voltage is chosen function of the supply inverter used, which has to have a rated current greater than the TF motor rated current.

The TF motor must have a simple air-gap and thus quite a simple construction. The specific output torque should be very high; the lower armature leakages and improved power factor are also specific targets. The experience accumulated and the results reported so far lead to the conclusion that the single-sided concentrating flux rotor machine topology matches all the previous requirements. Another item to be discussed here is the TF machine pole number. It is true that each additional stator pole structure means a further component of torque added to the total, but increasing the number of poles too much will lead to a reduced torque per pole and to a reduced torque per phase. The optimal pole number should be a result of 3D-FEM analysis, and it corresponds to the maximum output torque density. A designer should remember the fact that an increased number of poles, for the same rated speed, means increased frequency and thus increased losses in the iron core, permanent magnets and stator carrier, and also an increase in the stator reactance, which will lower the power factor value.

As far as the single-sided TF motor construction is concerned, the following aspects must be considered:

- The effective air-gap length is larger than the induction machine's, for instance, in the case of the reported prototypes [2,4,5,6], the air-gap length is about 1mm, the power being below 50 kW.
- Almost all prototypes reported so far have exterior rotor and interior stator, with a special water cooling arrangement. This looks like the optimum solution, the permanent magnets placed in the rotor core being cooled better.
- The stator and rotor carriers should be carefully chosen in order to avoid extra losses and increased leakages.
- The rotor poles should be made of composite material, since the flux has a 3D path.
- The permanent magnets must be made of very high energy magnetic material, almost all reported prototypes have permanent magnets from the NdFeB class with very good performances. The permanent magnet length on the flux direction has to be large enough to ensure the necessary MMF and to avoid the peril of demagnetization.
- The stator phase winding should be built up of small cross-section conductors to avoid the increase in phase resistance, an interesting solution being proposed in [4]. It is also desirable to have a high filling factor in order to reduce the stator slot area and thus the machine dimensions.

The main design specifications for a TF motor are: the phase rated output power (P_{out}), speed (n) and phase voltage (V). In order to start the dimensioning procedure, other values have to be chosen as well: the efficiency (η), power factor ($\cos\varphi$), electric loading (A_S), maximum air-gap flux density (B_{gmax}), air-gap length (g), and number of rotor poles (Q_R). The most important dimensioning estimation formulae are:

The sizing equation:

$$D_g^3 = \frac{P_{out}}{\eta k_l k_p k_B k_{ov} K_i K_L \pi^2 B_{g\max} A_S Q_R n} \tag{6}$$

with the aspect ratio factor K_L,

$$K_L = \frac{l_R}{D_g}$$

and with the sizing factors [14]:
k_l – a factor that considers the decreasing of the EMF due to armature reaction and increase in permanent magnets flux leakages
k_B – the air-gap flux density factor ($k_B = A_R / A_p$)
k_p – the stator pole length factor ($k_p = b_{sp} / \tau_S$)
k_{ov} – the overlap factor ($k_{ov} = l_{sp} / l_R$)

The permanent magnet height h_{pm}, which is defined in the magnetizing direction of the permanent magnet.

$$h_{pm} \geq g \frac{\mu_{pm}}{\mu_o} \frac{B_{g\max}}{B_r \frac{b_{pm}}{b_{Rp}} - B_{g\max}} \tag{7}$$

where μ_{pm}, μ_0 are the permeability of the permanent magnet and free space respectively, and B_r is the permanent magnet residual flux density.

The machine parameters:

- Stator phase winding resistance

$$R_S = \rho \frac{\pi (D_g - g - 2h_o - h_{Ss})}{A_{cond}} N_t \tag{8}$$

- Stator phase leakage inductance

$$L_{S\sigma} = \mu_o \pi (D_g - g - 2h_o - h_{Ss}) N_t^2 \left(\frac{h_{Ss}}{3w_{Ss}} + \frac{h_o}{w_{Ss}} \right) k_{L\sigma} \tag{9}$$

- Stator magnetizing inductance

$$L_{Sm} = k_{Lm} N_t^2 Q_S \frac{\mu_o A_R}{2\left(g + \frac{h_{pm}\mu_o}{\mu_{pm}} \right)} \tag{10}$$

- The torque and EMF per phase:

$$T_p = N_t \cdot I \cdot \Delta\phi \cdot \frac{Q_R}{\pi} Q_S \tag{11}$$

$$E_p = 2N_t \cdot \Delta\phi \cdot Q_R Q_S \cdot n \tag{12}$$

where:

$$\Delta\phi = k_{\sigma pm} \cdot \phi_{pm} - k_{\sigma coil} \cdot \phi_{coil} \tag{13}$$

$$\phi_{pm} = F_{pm} \frac{\mu_o A_R}{g} \tag{14}$$

$$F_{pm} = \frac{gB_r}{\mu_o} \frac{1}{1 + \frac{g}{h_{pm}} \frac{\mu_{pm}}{\mu_o}} \tag{15}$$

$$\phi_{coil} = N_t I \frac{\mu_o A_R}{2\left(g + \frac{h_{pm}\mu_o}{\mu_{pm}}\right)} \tag{16}$$

- Power factor:

$$\cos\varphi \cong \frac{E}{\sqrt{E^2 + (X_S I)^2}} \tag{17}$$

where the stator reactance X_S is:

$$X_S = 2\pi Q_S \cdot n(L_{Sm} + L_{S\sigma}) \tag{18}$$

All the formulae can be checked on the TF-SM1, and the results are given in Tab. 2., Tab. 1. containing the different factors' values, all being computed for the specific case of TF-SM1.

k_l	k_p	k_B	k_{ov}	K_I
0.95	0.8	1.25	1	1.43
$1/K_L$	$k_{L\sigma}$	k_{Lm}	$k_{\sigma pm}$	$k_{\sigma coil}$
17	3	1.5	0.55	0.4

Tab. 1. TF-SM1 design factors

Dg	Φpm	Φcoil	Tp	P
m	mWb	mWb	Nm	kW
0.2836	0.1421	0.0116	87.46	14.84
LSσ	LSm	XS	Emax	cosφ
mH	mH	Ω	V	-
0.6698	0.1523	1.86	67.9	0.447

Tab. 2. TF-SM1 estimated dimensions and characteristics

The TF-SM1 efficiency, maximum air-gap flux density and electrical loading are, respectively:

η=0.9; B_{gmax}=1.0 T; A_S=1460 A/m;

and the maximum phase EMF computed by 3D-FEM at no-load is E_{max}=116V.

The maximum phase EMF computed with (12) when Φ_{coil}=0 and $k_{\sigma pm}$=0.8 is:

$$E_{max} = 2 \cdot 16 \cdot 0.8 \cdot 1.421 \cdot 10^{-4}\,\mathrm{Wb} \cdot 9\tfrac{1}{s} \cdot 80 \cdot 40 = 104.77\,\mathrm{V} \tag{19}$$

which is quite close to the FEM computed value.

The permanent magnet flux leakage factor $k_{\sigma pm}$ has a different value at no-load operating, because the armature reaction and the saturation due to the armature current do not influence the permanent magnet flux leakage.

The measured power factor value for TF-SM1 at full load is cosφ ≅ 0.40, which is also close to the estimated value, given in Tab. 2.

As a conclusion, the estimation formulae produce quite acceptable values, the maximum difference in the case of TF-SM1 being about 10% for the output power.

Like any other conventional type of electric machine, the TF machine produces copper losses and iron losses in the stator and rotor core, and also losses in the permanent magnets and stator and rotor carriers. The copper losses computation is quite usual, but the iron core losses computation process is still under investigation. The proposed methods, with good specific results, cannot offer the required coverage of the phenomenon. It looks like a 3D-FEM transient solver would be a solution, but it requires quite long computational time and huge memory.

The first attempt in dealing with the iron losses calculation in the case of the TF machine is reported in [12], the losses being computed separately in the stator core, in the permanent magnets and in the stator carrier. A specific technique is used in [12] to compute the losses in the permanent magnets and in the stator carrier caused by the rotor movement, in the case of the TF-SM1. The effect of the stator slots is simulated by an arrangement of conductors placed in the air-gap and fed by an appropriate sinusoidal current. In this way the transient regime was transformed in a time-harmonic one and it could be solved quite easily. Based on the results obtained in [12], a simple loss estimation is proposed in [14] for a TF machine, assuming that a new TF machine has the same materials, permanent magnets and iron core as the TF-SM1. The results obtained in [14] for an estimation-design calculation are quite satisfactory, and thus the losses can be estimated based on the existing results for almost any new TF machine.

4. CONCLUSION

The TF motor has bigger torque both with respect to volume and to weight, compared to the conventional motors. Its quite complicated construction, even in the single-sided variant, is fully compensated by its good performance. Thus the TF motor seems to be very well suited for direct, variable speed drive systems. Being quite a newcomer in the electrical machines family, the TF motor can be an important development in the field, and further improvements are expected.

The paper discusses the single-sided TF motor, with more strength on the machine mathematical model, construction and design. The comprehensive presentation covers the main aspects of the single-sided TF motor, offering a guideline for the user or designer of such a motor.

5. ACKNOWLEDGEMENT

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7. APPENDIX

The TF-SM1 main data and dimensions

Rated output power [kW]	17
Rated supply voltage [V]	380
Rated phase current [A]	73
Rated speed [rpm]	540
Rated torque [Nm]	300
Number of pole pairs	40
Air-gap diameter [m]	0.255
Air-gap length [mm]	0.8
Stator length [m]	0.18
Number of winding turns	16

Tab. A1. TF-SM1 main data

A_p	m^2	$0.12 \cdot 10^{-3}$	b_{Rp}	m	0.01
A_R	m^2	$0.15 \cdot 10^{-3}$	b_{pm}	m	0.01
b_{Sp}	m	$8 \cdot 10^{-3}$	h_{pm}	m	0.0042
τ_S	m	0.01	h_0	m	0.015
l_{Sp}	m	0.015	h_{Ss}	m	0.02
l_R	m	0.015	w_{Ss}	m	0.02

Tab. A2. TF-SM1 dimensions

8. MAIN NOTATION LIST

A_p - stator pole area [m^2]
A_R - rotor pole area [m^2]
A_S - electrical loading [A/m]
B_{pm} - permanent magnet flux density [T]
B_r - residual flux density of the permanent magnet [T]
b_{Rp} - rotor pole width [m]
b_{Sp} - stator pole width [m]
b_{pm} - rotor permanent magnet length [m]
D_g - air-gap diameter [m]
E_{max} - stator phase maximum no load EMF [V]
E - stator phase EMF induced by rotor magnetic field variation [V]
F_{pm} - permanent magnet MMF [A]
g - air gap length [m]
H_c - coercive force [A/m]
h_0 - stator slot height unoccupied by conductors [m]
h_{pm} - permanent magnet height [m]
h_{Sp} - stator pole height [m]
h_{Ss} - stator slot occupied by conductors height [m]
I - stator phase rms current value [A]
k_I, k_B, k_p, k_{ov}, K_I, K_L - sizing equation factors
k_{Lm}, $k_{L\sigma}$ - inductance factors
$k_{\sigma coil}$, $k_{\sigma pm}$ - pole flux factors
l_R - rotor axial length [m]
l_{Sp} - stator pole axial length [m]
L_{sm} - stator phase winding magnetizing inductance [H]

$L_{s\sigma}$ - stator phase winding leakage inductance [H]
n - rotor speed [1/s]
N_t - stator phase winding number of turns
P_{out} - output phase power [W]
Q_R - rotor number of poles
Q_S - stator number of polar pieces
R_S - stator phase winding resistance [Ω]
T - torque per phase [Nm]
X_S - stator phase reluctance [Ω]
ϕ_{pm}, ϕ_{coil} - fluxes [Wb]
ρ - electric resistivity [Ω]
μ_0 - free space permeability [H/m]
μ_{pm} - permanent magnet permeability [H/m]
θ - rotor angular displacement [rad]
η - efficiency
τ_R - rotor pole pitch [m]
τ_S - stator pole pitch [m]

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