Transverse flux motor drive dynamics

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Abstract **– The transverse flux motor (TFM) can be an important competitor on the variable-speed-direct-drive domain due to its very high torque density. The transverse flux reluctance motor (TFRM) is the simplest structure of the TFM class. The TFRM's mathematical model is developed in the paper and the motor's dynamic regime is studied via MATLAB/SIMULINK software environment.**

I. INTRODUCTION

The TFR machine is a variant of the TF machine with passive rotor. The TFRM has a ring winding with salient poles on the stator and only salient poles on the rotor.

A part of a TFRM phase module, given in linear layout for better understanding, is given in Fig. 1.

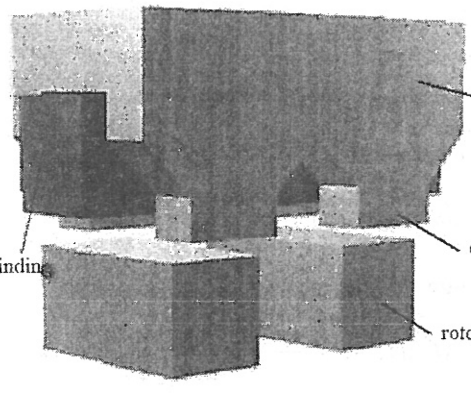


Fig. 1. A part of a TFRM phase model [2]

The TFRM has quite the same features as the switched reluctance motor (SRM), the main differences consisting in the homopolar stator ring winding and the equal number of poles on the stator and rotor [1, 2]. As in the case of all TFM's each TFRM phase is an independent machine, the phase modules being placed one after another on the axial direction. In Fig. 2 the TFRM's phases have a common yoke but they can be totally independent.

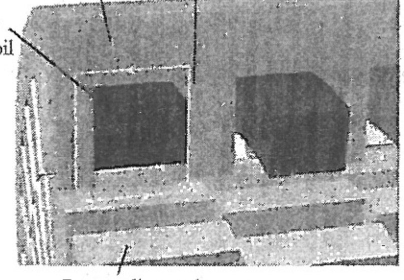


Fig. 2. A TFRM with common yoke for the phases [2]

If the stator poles are aligned for all phases then the rotor poles must be shifted adequately to obtain the necessary spatial displacement. TFRM must have three or more then three phases in order to avoid start-up difficulties and to obtain continuous rotation. The TFRM has to be supplied by a power electronic converter, which gives unipolar pulses precisely synchronized with the rotor position. The converter, usually of asymmetric half bridge type, is quite the same as for the SRM [2]. Such a converter assures an independent current variation on each phase.

The TFRM behaves as the SRM and its control is quite similar. The TFRM requires rotor position sensing to control the current commutation from phase to phase. An encoder attached to the shaft supplies usually the rotor position, but a specific technique for indirect sensing can be applied.

A performant drive system cannot be obtained only with very well designed and constructed motors. It requires a suitable power electronic converter and adequate torque, speed and current controllers. Computer simulation of the entire drive system enables verification of the motor design and of the drive system ability to match the load torque over the entire speed range in steady-state and transient regime. The steady-state regime can be covered adequately with the simplified mathematical model used for design-estimation, or by finite element (FEM) analysis [2, 3]. Simulation of the entire drive system requires the mathematical model of the TFRM and of the other components as well as their interconnections. Some attempts to present the TFRM mathematical model were previously made [4, 5, 6], but they did not cover entirely the subject. In this paper the TFRM mathematical model is studied on analytical base, as well as by simulation via the MATLAB/SIMULINK programming environment.

II. THE TFRM MATHEMATICAL MODEL

The TFRM has independent phases, then its mathematical model is given by the equations:

$$v = R \cdot i + \frac{d\lambda}{dt} \tag{1}$$

$$\lambda = L(\theta, i) \cdot i \tag{2}$$

$$T = \frac{\partial W_m}{\partial \theta} = \frac{d}{d\theta} \int_0^i \frac{1}{2} \lambda(\theta, i) \cdot di \tag{3}$$

$$T = J\frac{d\Omega}{dt} + T_f + T_l \tag{4}$$

where v, i, λ and R are the phase voltage, current, flux linkages and resistance and T, T_l, T_f are the electromagnetic, load and friction torque respectively.

The rotor position electric angle θ is given by the equation:

$$\frac{d\theta}{dt} = \omega = p \cdot \Omega \tag{5}$$

where the number of pole pairs p is equal to the number of stator, or rotor, pole pieces, $Q_S = Q_R$.

The friction torque depends on the machine speed, but usually it has smaller value and is neglected against the load torque at low speed.

The TFRM design procedure implies, quite usually, a FEM analysis and consequently the variation of the phase flux linkages and torque function of the rotor angular position and phase current are known. These can be used in computing the steady-state or dynamic characteristics of the TFRM. As was proved in [3, 5] there is an 3D to 2D equivalence for TFRM and the FEM analysis can be performed on the 2D equivalent structure.

Based on the given mathematical model (1)÷(5) and on the flux linkages and torque characteristics computed, via a 3D or 2D FEM analysis, function of phase current and rotor angular position in [5] and [6] the TFRM dynamic regime was simulated via SIMULINK and SIMPLORER respectively. In the SIMULINK program the characteristics obtained by FEM computation were introduced as look-up tables. The SIMPLORER program was linked to the FLUX 3D FEM software and the computation was done in the same time in both programming environments.

In the following a simplified mathematical model, which does not require FEM analysis results to operate with, is proposed. In this model, in order to obtain the inductance and torque variation function of current and rotor angular position, an air-gap variable equivalent permeance is defined as:

$$P(\theta, i) = \frac{1}{g^*}(1 + P_R \sin\theta) \tag{6}$$

where P_R is the permeance coefficient with slots considered only on the rotor, [2]:

$$P_R = \frac{4}{\pi} \cdot \beta \cdot k_{CR} \cdot \sin\left(\frac{\gamma}{\beta} \cdot \frac{g}{\tau_R} \frac{\pi}{2}\right) \tag{7}$$

$$\beta = \frac{(1-f)^2}{2(1+f^2)} \tag{8}$$

$$f = u + \sqrt{1+u^2}, \quad u = b_{Rs}/2g \tag{9}$$

$$\gamma = \frac{4}{\pi}\left(u \cdot tg^{-1}u - \ln\sqrt{1+u^2}\right) \tag{10}$$

The equivalent air gap g^* is:

$$g^* = k_{CR} \cdot k_s \cdot g \tag{11}$$

with the Carter's factor is given by:

$$k_{CR} = \frac{\tau_R}{\tau_R - \gamma \cdot g} \tag{12}$$

where τ_R is the rotor pole pitch and b_{Rs} the rotor slot width

The saturation factor k_s depends on the phase current and can be computed in aligned position, as

$$k_s = f(i) \tag{13}$$

The variable air-gap flux density is:

$$B_g(\theta, i) = F \cdot \mu_0 \cdot P(\theta)$$
$$B_g(\theta, i) = F \cdot \mu_0 \cdot \frac{1}{g^*}(1 + P_R \sin\theta) \tag{14}$$

where F is the phase MMF.

The maximum value of the air-gap flux density occurs at aligned position,

$$B_{g\max}(i) = B_g(\theta, i)_{\theta=\pi/2} = F \cdot \mu_0 \frac{1}{g^*}(1 + P_R) \tag{15}$$

and consequently:

$$B_g(\theta, i) = B_{g\max}(i) \frac{1 + P_R \sin\theta}{1 + P_R} \tag{16}$$

The phase inductance is:

$$L(\theta, i) = \frac{\lambda(\theta)}{I} + L_{S\sigma} \tag{17}$$

where $L_{S\sigma}$ is the phase leakage inductance, which is considered constant.

Finally comes:

$$L(\theta, i) = M_d(i) \frac{1 + P_R \sin\theta}{1 + P_R} + L_{S\sigma} \tag{18}$$

with the aligned inductance M_d,

$$M_d(i) = \frac{B_{g\max}(i) \cdot N \cdot A_p \cdot Q_S}{I} \tag{19}$$

N, A_p and I being the phase number of turns, the stator pole area and the phase rms current.

By now the flux linkages derivative can be computed as:

$$\frac{d\lambda(\theta, i)}{dt} = L(\theta, i)\frac{di}{dt} + i\frac{\partial L(\theta, i)}{\partial\theta} \cdot \frac{d\theta}{dt} \tag{20}$$

which leads to:

$$\frac{d\lambda(\theta, i)}{dt} = \left(M_d(i) \frac{1 + P_R \sin\theta}{1 + P_R} + L_{S\sigma}\right)\frac{di}{dt} + \\ + \omega M_d(i) \frac{P_R \cos\theta}{1 + P_R} \cdot i \tag{21}$$

The electromagnetic torque is then:

$$T = \frac{\partial W_m}{\partial\theta} = k_T \cdot i \cdot \cos\theta \tag{22}$$

with

$$k_T = \frac{N}{2} \cdot Q_S^2 \cdot A_p \cdot \frac{P_R \cdot B_{g\max}}{1 + P_R} \tag{23}$$

The proposed simplified mathematical model contains the equations (1), (4), (21) and (22) with the necessary computations done via (7)-(12), (19) and (23).

III. TFRM DYNAMICS SIMULATION, CONCLUSIONS.

The entire TFRM drive system is simulated based on MATLAB/SIMULINK software environment. It means that, for only one phase current duty cycle, the hysteresis current controller and the asymmetric half bridge electronic converter were simulated together with TFRM. The considered dynamic regime is the run on regime for one stroke. The main data of the TFRM are given in Table I.

TABLE I.

Rated power [kW]	24
Rated phase voltage [V]	260
Rated phase current [A]	170
Maximum phase current [A]	200
Efficiency	0.95
Power factor	0.65
Moment of inertia [kgm^2]	3.29
Number of pole pieces	40
Air-gap diameter [m]	0.33
Length per phase [mm]	60
Rotor slot width [mm]	13
Number of turns per phase	12
Phase leakage inductance [mH]	0.314
Air-gap length [mm]	0.6

The SIMULINK model of the TFRM is given in Fig. 3.

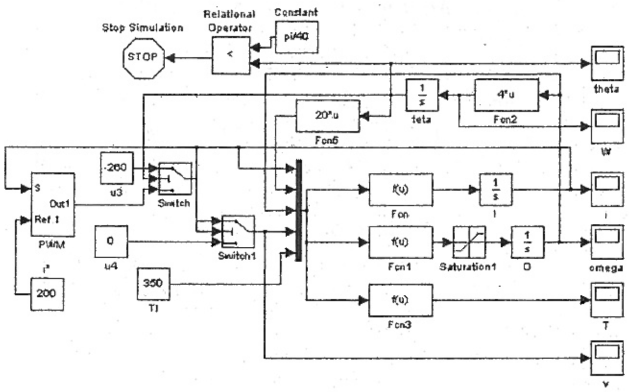


Fig. 3. The SIMULINK model of the TFRM

The model is based on the following equations:

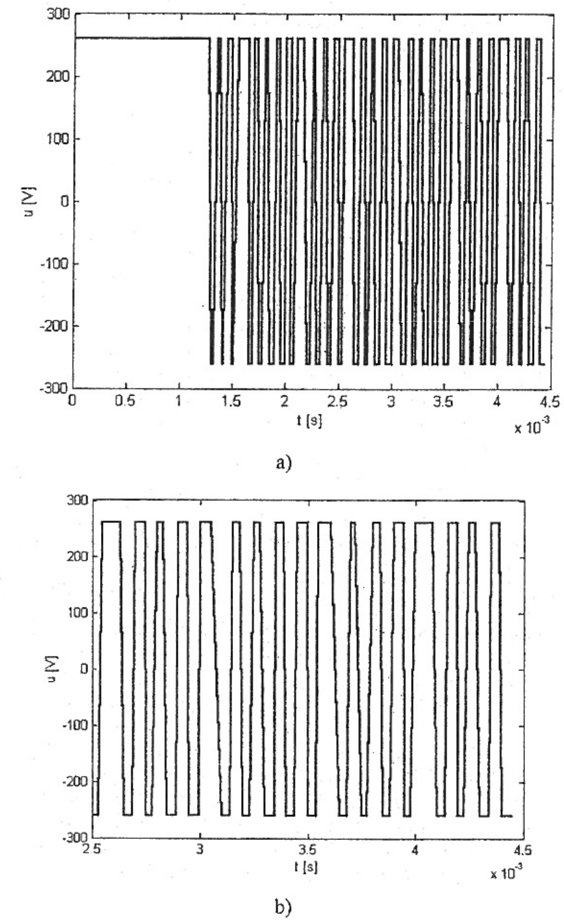
$$\frac{di}{dt}=\frac{v-\left(R+Q_R\cdot\Omega\cdot M_d\,\dfrac{P_R\cos\theta}{1+P_R}\right)i}{\dfrac{M_d}{1+P_R}\left(1+P_R\sin\theta\right)+L_{S\sigma}} \tag{24}$$

$$\frac{d\Omega}{dt}=0.3\left(K_T\cdot i\cdot\cos\theta-T_l\right) \tag{25}$$

$$\begin{aligned} k_s &= f(I),\\ M_d &= 2.08\cdot10^{-3}\,f(i),\\ K_T &= 2.41 f_2(I)\end{aligned} \tag{26}$$

Some results obtained for a run up when the rotor initial position is unaligned, θ=0, and the final one is aligned, $\theta=\pi/2$, are given in the next figures.

The phase voltage variation function of time is shown in Fig. 4a. In Fig. 4b for better understanding purpose a zoom of the conduction period's end is given.



a)

b)

Fig. 4. Phase voltage variation

The current, Fig. 5, is kept almost constant at its maximum value.

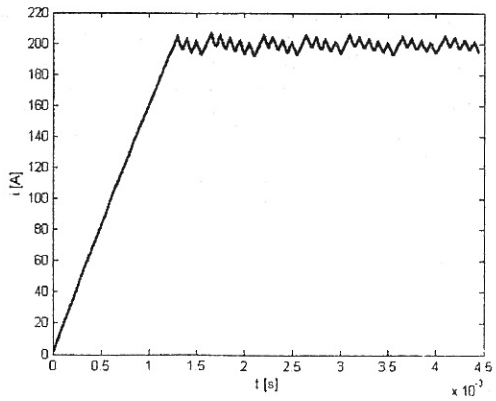


Fig. 5. Phase current variation

The plot of the rotor speed versus time is given in Fig. 6.

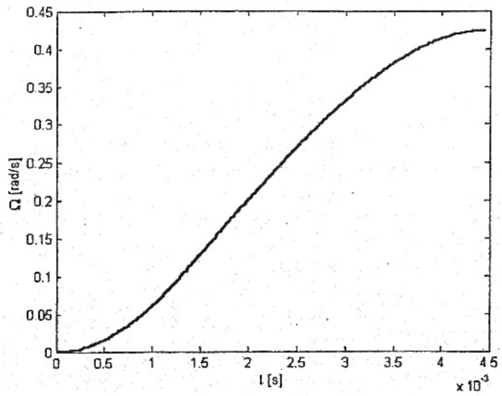


Fig. 6. Rotor speed variation

The angular displacement of the TFRM is given in Fig. 7.

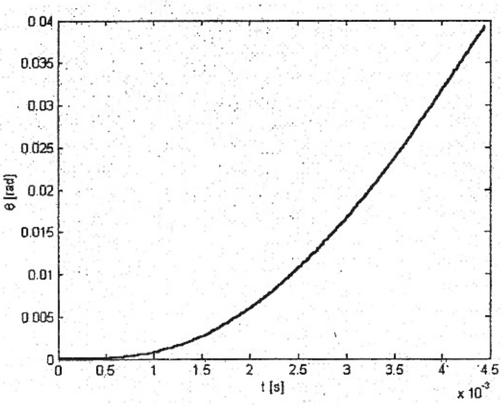


Fig. 7. Angular displacement variation

The torque increases quite fast and varies almost cosinusoidally since the current is kept constant, Fig 7.

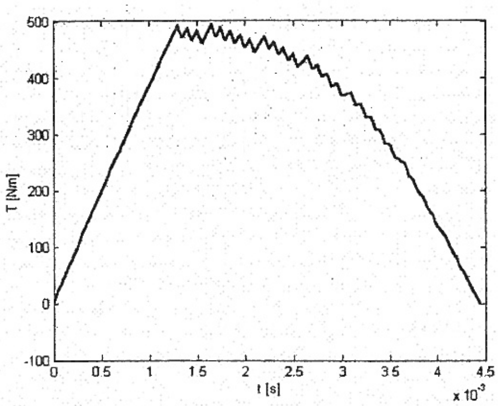


Fig. 8. Torque variation

Since the current is kept almost constant at the maximum value, k_s is constant too, and consequently M_d and K_T have a fixed value computed with the maximum stator MMF.

The proposed mathematical model is simple and quite accurate. It is well fitted for dynamic regime study, as it comes out from the given simulation results.

IV. ACKNOWLEDGEMENTS

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