On the Transient Modelling of PM Motors

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Abstract: - A model for a PM electric motor describing transient operation is presented. The paper provides an outline of the equivalent magnetic circuit modelling method used and the model parameters for a Permanent Magnet motor. The operation of a 40 kW motor-generator is used to illustrate the model accuracy compared with results provided by a conventional analytical model. The advantage of the proposed electric motor model is that it is computationally inexpensive, yet offers high accuracy.

Key-Words: - Modelling, permanent magnet motor

1 Introduction

Performance simulation is important to assess various parameters for any electric drive configuration as well as for the specification of its components. Such simulation is particularly useful for electric motors, considering the wide range of types and topologies of machines available. However, if the simulation is to be both accurate and reliable as a prediction of real-world performance, it requires accurate computer-based models of the components involved.

An electric motor model is important as in many electric drives' configurations. The motor is constantly in operation, whereas other electric drives' components might not be. This operation is usually transient, in both speed and load. Very often, an electric machine operates at light load, and the efficiency is largely dependent on no-load losses.

Existing electric motor models typically consist of a "look-up" table with operating points for speed and torque that have been measured under steady-state conditions. This presents two problems:

- Electric motor operation in electric drive is usually under transient conditions, not steady-state so the model may not represent real-world operation; and
- A prospective motor design must be manufactured and measured to provide operating data before it can be assessed as part of the drive.

Furthermore, during the design of an electric drive, the configuration and component sizes must be selected and a parametric study is useful. "Optimiser" functions in software typically resize components by iteration to achieve the desired drive design. This resizing is achieved by scaling the steady-state performance map, rather than scaling the motor design to obtain a new performance map.

An established technique for evaluating electric motor designs is to use an equivalent magnetic circuit model [1]. This is a development of classical electromagnetic design techniques by evaluation of the flux paths within the machine. These paths are determined by the magnetic properties of the materials, such as the electrical steel and copper windings, and the geometry of the air gaps, etc. The instantaneous evaluation of the operation allows transient analysis with a performance history. Efficiency maps obtained from steady-state testing at ambient temperature do not accurately represent the transient performance or operation at elevated temperatures.

A more accurate method of modelling electric motor performance is by Finite Element Method, but this method is computationally very expensive [2]. The equivalent magnetic circuit model lends itself well to performing parametric studies because it can define transient performance quickly. This provides a more accurate sizing function than scaling an existing performance map. For these reasons, this technique deals with the problems described above and has been selected for the present motor component modelling.

To obtain an equivalent magnetic circuit model of the motor the following constraint input data and either of the operation data with respect to time have to be known:

- Specified constraints – the electromagnetic geometry, ambient and starting temperature,
- Specified operation – torque and speed demand, or voltage supply.

The output data required is the following:

- Operating characteristics –voltage and phase current (for torque and speed specified operation) to deliver the specified operation, or mechanical operation (for voltage supply specified operation),
- Performance measures – temperature, efficiency.

2 Equivalent Magnetic Circuit Modelling

Equivalent magnetic circuit modelling solves the relation between flux, reluctance and magneto-motive force, $[\Phi] = [R]^{-1} [F]$, for the flux paths within the motor, where $[\Phi]$ is a matrix of magnetic fluxes, $[R]$ is a matrix of reluctance values and $[F]$ is a magneto-motive force (m.m.f.) matrix.

Each individual part of the magnetic flux paths are modelled as reluctance, R, and these are connected together. Such reluctances represent the main flux paths and leakage and fringing flux paths. M.m.f. sources, such as current-carrying coils, and flux sources, such as permanent magnets, are incorporated into the equivalent circuit. The useful flux is then derived using a technique, such as Norton equivalent circuit or Kirchoff's voltage law.

The construction of the circuit is made according to the electromagnetic geometry (the specified constraints). This defines values within $[R]$. Values within $[F]$ and $[\Phi]$ change with respect to the specified operation and the operating characteristics.

The selected modelling method has traditionally been used to determine open circuit flux linkage, which is used to find the induced e.m.f., by including the rotor flux sources while omitting the stator m.m.f. sources. It is alternatively used to find the reaction field and stator inductance, by including the stator m.m.f. sources and not the rotor flux sources. This calculation provides the demagnetising field against permanent magnets. In using the modelling method here, both rotor flux sources and stator m.m.f. sources are included to find the operating flux linkage, giving the terminal voltage rather than the induced e.m.f., and the current.

However, a limitation of equivalent magnetic circuit modelling is that the R-Φ relation is linear for an unchanged m.m.f., which assumes no magnetic saturation. In practice, ferromagnetic materials have non-linear magnetic properties, defined by *B-H* curves. In the model proposed smaller individual parts to the flux paths and a maximum limit to the magnetic flux density account for the saturation in non-linear materials.

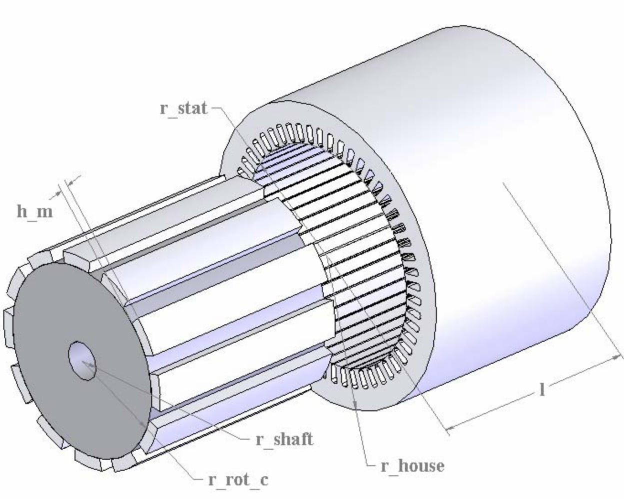

Figure 1: A PM motor with the geometric parameters required for the specified constraints.

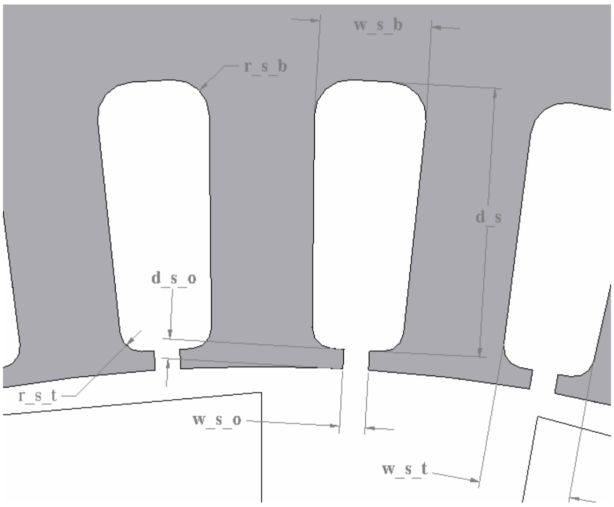

Figure 2: PM motor detailed geometric parameters required for the specified constraints.

3 Permanent Magnet Motor Parameters

The proposed version of the motor component model is for Permanent Magnet (PM) motors, although the modelling method is not exclusive to this motor type. Figures 1 and 2 provide an image of such a motor, with the motor parameters used to define the electromagnetic geometry. These, along with material properties and operating conditions, which comprise the input data, are given in Table 1.

Table 1: Brushless PM motor dimensions and parameters.

Numeric values	Number rotor pole pairs	p
	Number phases	m
	Number slots per pole per phase	q
	Number stator poles	
	Number of turns per pole	N
Mechanical dimensions [mm]	Machine length	l
	Airgap mechanical clearance	g
	Radius shaft	r_shaft
	Radius rotor core	r_rot_core
	Magnet height	h_m
	Radius stator	r_stat
	Radius housing	r_house
	Depth slot opening	d_s_o
	Depth slot	d_s
	Pole pitch ratio	k_p_pitch
	Width slot opening	w_s_o
	Width slot top	w_s_t
	Width slot bottom	w_s_b
	Radius slot top	r_s_t
	Radius slot bottom	r_s_b
Electromagnetics	Magnet coercive force	H_c
	Magnet residual flux density	B_r
	Magnet relative permeability	mu_r
	Lamination factor	k_lam
	Lamination B-H function	B=f(H)
Operating conditions	Mechanical speed [rpm]	omega_mech
	Torque [Nm]	T
	Phase current rms [A]	I_ph
	Phase voltage line-neutral rms [V]	V_ph

An area part of the motor is discretised to form the parts of the individual flux paths, as shown in Fig. 3, which have reluctances values used in [*R*]. The additional paths that extend outside the geometry are for leakage flux circuits.

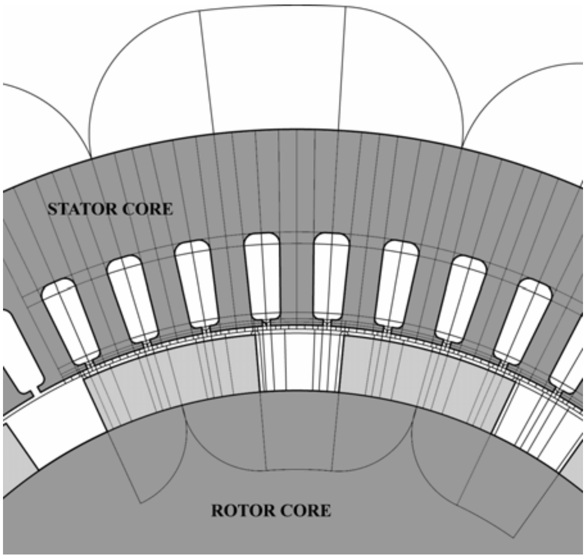

Figure 3: Discretised area of the motor, with multiple reluctances for the airgap.

The usual equivalent magnetic circuit modelling method defines the airgap reluctance path as a single reluctance over the width of a rotor pole. This gives a mean value for the airgap flux used to find the useful flux. The value is an overestimate if airgap leakage is neglected, which ignores stator slotting and other perturbations to the airgap permeance function. Therefore, to account for these variations, multiple parallel reluctances are used to model the airgap, as shown in Fig. 4, which is a technique demonstrated in [3]. An approximation of the waveform of the airgap flux density is now available, rather than an assumed square waveform, as in the ideal Brushless PM machine, making it possible to determine variation in copper and iron losses.

Table 2: Linear characteristics of flux path reluctances.

Airgap	Linear	B=mu_0*H
PM poles	Linear	B=mu_r_PM*H
Stator core	Saturable	B=f_stat_core(H)
Rotor core	Saturable	B=f_rot_core(H)
Stator winding	Linear	B=mu_r_Cu*H

Figure 4 shows a simplified version of the equivalent magnetic circuit. The leakage path reluctances are included for the stator and rotor at the top and bottom of the figure respectively. The coils provide the stator m.m.f sources F_c and the permanent magnets provide the rotor flux sources Φ_0 in parallel with magnet reluctance R_m. The multiple airgap reluctances are represented by R_{a1} … $R_{a\ i}$. Several reluctances for airgap leakage paths are also included.

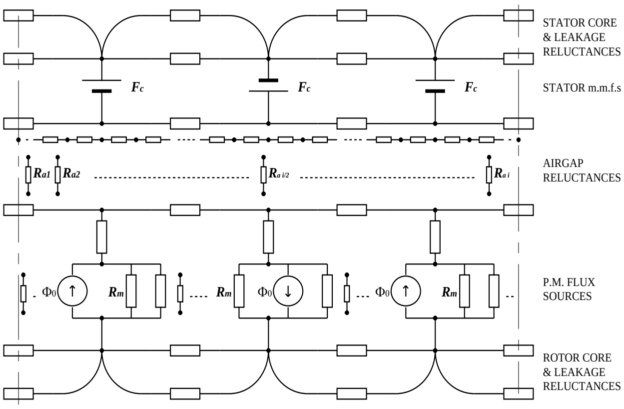

Figure 4: A simplified version of the equivalent magnetic circuit.

The model circuit presented can be linked to an equivalent thermal circuit model, which will return temperature data. This can be used to update the values for electric operation, which affect [*F*].

The unknown components of the equivalent magnetic circuit model matrices must be recognised and solved by iteration according to the known matrix components. A common computer software for matrix manipulation is Matlab®. This is also convenient for time-based simulation, with use of the Simulink® toolbox. However, the equivalent magnetic circuit model of the motor component may be used in any software language.

4 Results

A motor-generator rated up to 40 kW at 2500 rpm was selected to evaluate the results calculated by the proposed model. The machine is a double-sided axial flux, surface mounted PM machine with an airgap winding.

Figure 5 provides a comparison between values for the terminal voltage and those found by conventional analytical calculations. These cover an operating speed between 0 and 4000 rpm and electrical power output of 0 (open circuit), 10 and 20 kW. The results illustrate the model’s accuracy is higher as it accounts for airgap leakage paths, which are significant in the motor selected. The relevant airgap flux density may be extracted from the model and a similar variation is found.

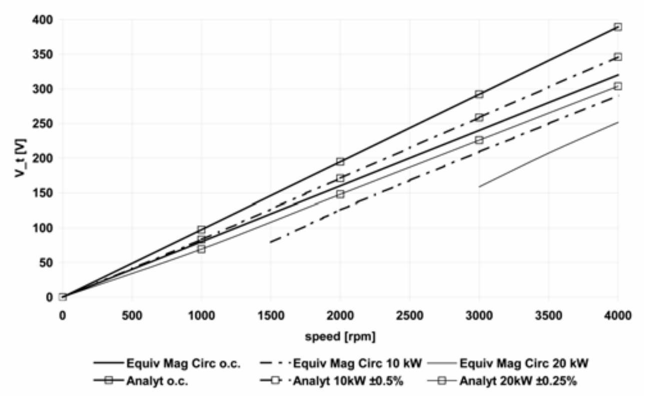

Figure 5: Equivalent magnetic circuit model and conventional analytical calculations of terminal voltage for a 40 kW motor-generator.

5 Conclusion

A model for transient performance of an electric motor component in a electric drive is proposed. The model is computationally inexpensive, allowing for use as part of the time-based electric drive performance calculation. The model is also flexible enough to facilitate parametric design studies.

The option for coupling with a thermal model gives further representation of real-world transient performance. The comparison of terminal voltage values for varying operating speed and power against classic analytical calculations indicate the good model accuracy.

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