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Analysis of coreless stator axial flux permanent magnet synchronous generator characteristics by using equivalent circuit

***Abstract**. This paper presents calculation procedure to predict the characteristics in coreless stator axial flux permanent magnet synchronous generators with surface mounted permanent magnets and double external rotor by using equivalent circuit. The input data for the calculation procedure are obtained from the measurements. The characteristics obtained by using measurements and equivalent circuit are in good agreement with analytically calculated results.*

***Streszczenie.** Artykuł przedstawia procedurę obliczeń przy użyciu schematu zastępczego do predykcji charakterystyki w bezrdzeniowych stojanach silników synchronicznych z magnesem trwałym o strumieniu osiowym z powierzchniowo zamontowanym magnesem i podwójnym wirnikiem zewnętrznym. Dane wejściowe do procedury obliczeniowej otrzymane są z pomiarów. Charakterystyki otrzymane z pomiarów i i z obliczeń pozostają w dobrej zgodności. (**Analiza bezrdzeniowego stojana generatora synchronicznego z magnesem trwałym i strumieniem osiowym za pomocą obwodu zastępczego**)*

Keywords: synchronous generator, permanent magnet, axial flux, equivalent circuit.
Słowa kluczowe: generator synchroniczny, magnes trwały, strumień osiowy, obwód zastępczy

Introduction

The analysis of the dynamic performance of an electromotor drive requires the employment of a dynamic model. The model may be either magnetically non-linear with defined parameters in a non-linear manner [1], or it may be linear with either variable or constant parameters, depending on the required drive performance and accuracy [2,3].

Although the extensive work required by finite element method (FEM) is often needed to calculate the exact magnetic flux distribution in the machine structure and electromotive force (EMF) in the windings, important results can still be expected from modelling approaches based on classical equivalent circuits [4].

Equivalent circuit models of a synchronous machine play an important role in the study of all characteristics including transient phenomena and stability of synchronous generators. Nowadays the machine capacity has increased and the accurate estimation of characteristics by using equivalent circuit has become important [5].

Axial flux permanent magnet motors are suitable for pumps, electrical vehicles, fans, valve control, centrifuges and industrial equipment. Axial flux permanent magnet machines can also operate as small to medium power generators. The large diameter rotor with its high moment of inertia can be utilized as a flywheel. Because large number of poles can be accommodated, these machines are ideal for low speed applications, i.e. electromechanical traction drives, hoists or wind generator [6]. Axial flux permanent magnet synchronous generators (AFPMSGs), which are also called disc machines, can replace their radial flux cylindrical shaped counterparts. Disc-shaped AFPMSGs can be built into the applications where conventional generators cannot be applied due to the lack of space in the axial direction. With the appropriate design, including housing, adjusted to specific applications, the AFPMSG can reach very high power density and compact construction. In contrast to radial flux machines, AFPMSGs can be designed as single-sided, double-sided with double external stators or rotors, and axial flux machines with multiple stators and rotors on the same shaft. The internal stator of a double-sided AFPMSG can be designed with an iron core or entirely without iron.

This paper presents calculation procedure to predict the characteristics in coreless stator AFPMSGs with surface mounted permanent magnets and double external rotor (Fig.1) by using equivalent circuit. The input data for the calculation procedure are obtained from the measurements by using measurement setup presented in Fig. 2 and Fig. 3, analytical results based on Maxwell's equations and results obtained by finite element method.

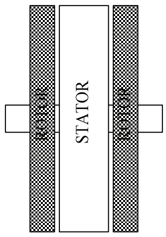

Fig.1. Topology of double-sided coreless stator AFPMSG

Measurements of AFPMSG characteristics

The major difficulty in the PM synchronous machine parameter measurements is due to the impossibility of removing the field excitation. The classical electrical parameter identification methods for wound-field synchronous machines cannot be used. In the literature, there are several papers presenting how the d–q equivalent circuit parameters can be determined by standstill test response. Since the standstill test does not reflect the machine real operative conditions, the load test must be also performed [7].

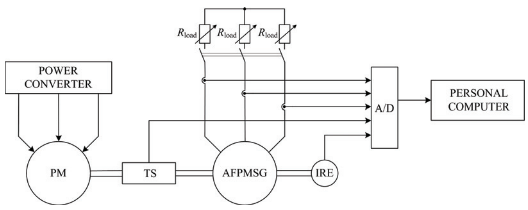

Fig.2. Scheme of AFPMSG experimental setup

Rotor shaft of AFPMSG is connected with incremental rotary encoder (IRE) which is needed for the characteristics measurements in dependency on rotor position. By using the personal computer and control system dSpace the angular dependency of the generator characteristics can be observed as a time dependant instantaneous values of electrical quantities (Fig. 2, Fig. 4 and Fig. 5). AFPMSG characteristics can be measured simultaneously and the interaction between them can be observed at every measured point.

The constant angular velocity of AFPMSG is assured by the prime mover (PM) fed by the power converter. Due to the AFPMSG rotor rotation the back EMF is induced in the stator winding. When the symmetrical three phase ohmic load (R_{load}) is connected to the generator the EMF causes the electrical current which flows through the winding and variable ohmic load consisted of three Y connected sliding resistors. In order to measure shaft torque the torque sensor (TS) is installed on the shaft between prime mover and AFPMSG. Specifications of measured AFPMSG are presented in Table 1.

Table 1. Specifications of AFPMSG

Section	Item	Value (unit)
Rotor	Disk radius	150 (mm)
	Height of PM	5 (mm)
	Angle of PM	25 (deg)
	Inner radius of PM	80 (mm)
	Outer radius of PM	150 (mm)
	Remanence of PM (B_r)	1,22 (T)
	Pole pitch (τ_p)	36 (deg)
	Number of pole pairs (p)	5
Stator	Current (I)	20 (A)
	Turns number (N)	50
	Number of coils	12 (2 x 6)
	Coil area width(τ_w)	20 (mm)
	Coil area height	7 (mm)
	Coil pitch	30 (deg)
Air-gap	Mechanical air-gap	1 (mm)

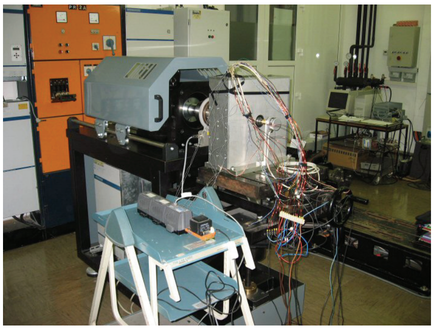

Fig.3. Experimental setup of AFPMSG

Fig. 4 presents the linear dependency between electrical angle and time. Instead of measured electrical angle the mechanical angle can be obtained from electrical angle divided by the number of AFPMSG pole pairs.

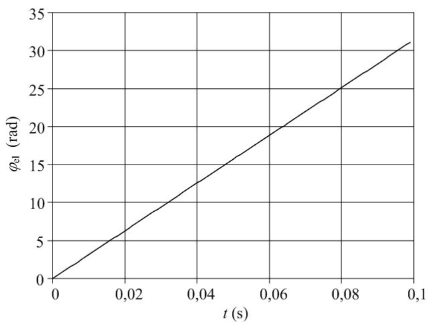

Fig.4. Time dependent measured electrical angle of AFPMSG

Due to the non-ferromagnetic supporting stator structure and relatively large diameter of AFPMSG rotor discs which cause high moment of inertia the constant angular velocity within one revolution is achieved (Fig. 5). Therefore, there is negligible difference between the time and angular dependency of measured results.

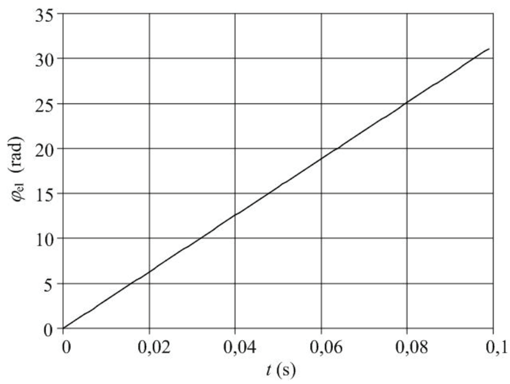

Fig.5. Time dependent measured angular velocity of AFPMSG

Equivalent circuit

Fig. 6 presents the equivalent circuit of the synchronous generator with surface mounted permanent magnet rotor and coreless stator. Based on the equivalent circuit from Fig. 6, which matches one phase circuit with ohmic load (R_{load}), the phasor diagram for the first harmonic component is presented in Fig. 7 and voltage equation can be determined as in (1), where $\underline{E}_0$ is back electromotive force (back EMF), $\underline{U}$ is terminal phase voltage, $\underline{I}$ is phase current, R_{ph} is phase resistance of the armature winding and X_d is synchronous reactance.

$$\underline{E}_0 = \underline{U} + \mathrm{j}X_d \underline{I} + R_{ph} \underline{I} \qquad (1)$$

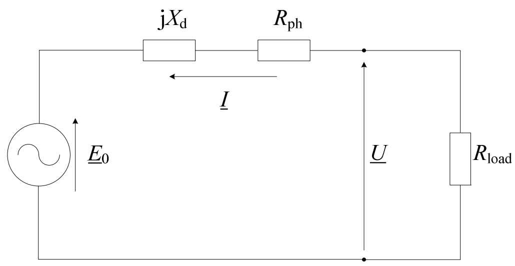

Fig.6. Equivalent circuit of AFPMSG

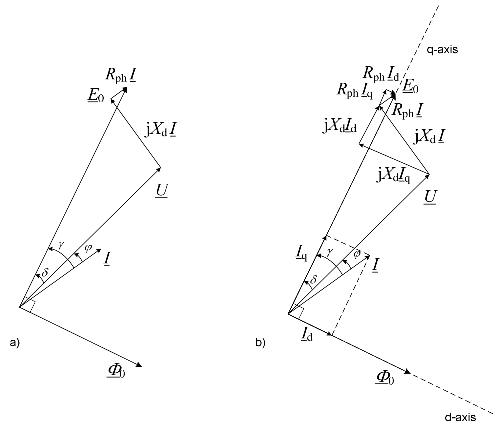

Fig.7. Phasor diagram: a) natural coordinate system, b) d-q coordinate system

Reluctances X_d and X_q (Fig. 7b) in d and q axes of AFPMSG model are of the same value. For this reason the reluctance torque is zero and the second term in (2) can be removed. The remaining term is synchronous torque (3), where p is the number of pole pairs, ω is electrical angular velocity, U is RMS terminal voltage of AFPMSG, E_0 is RMS phase back EMF and δ is angle between $\underline{E}_0$ and $\underline{U}$.

(2) $$M = -\frac{3p}{\omega}\left(\frac{UE_0}{X_d}\sin\delta + \frac{U^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta\right)$$

(3) $$M = -\frac{3p}{\omega}\frac{UE_0}{X_d}\sin\delta$$

In d-q model, the torque calculated from (3) can be determined as (4) or (5).

(4) $$M = \frac{3p}{\omega}E_0 I_q$$

(5) $$M = \frac{3p}{\omega}E_0 I\cos\gamma$$

Results and discussion

Due to the nonmagnetic supporting stator structure and symmetrical excitation distribution, the phasors in Fig. 7 can be directly compared with time-dependent voltages and currents (Fig. 8). Instantaneous induced phase voltage at load conditions (e_{load}) is calculated by using (6), where u is instantaneous terminal voltage and i_{ph} instantaneous phase current. The average angle γ between the induced voltage at no-load conditions and phase current can be obtained from the measurements (Fig. 7). By any load change the angles, including γ, have to be recalculated.

(6) $$e_{load} = u + i_{ph}R_{ph}$$

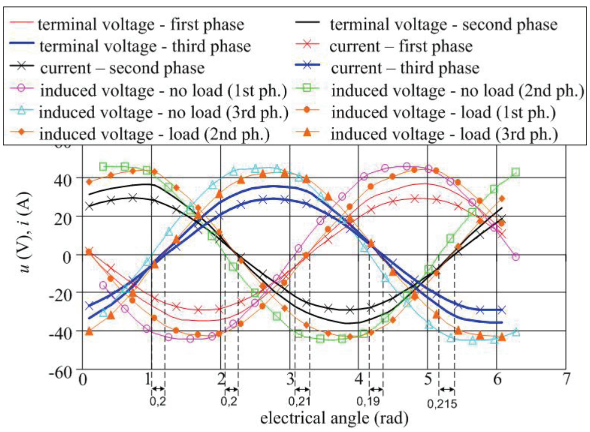

Fig.8. Measured instantaneous current, induced voltage at no-load conditions, terminal voltage and calculated induced voltage at load conditions

Fig. 9 presents an interdependences of back EMF waveform, analytically calculated and measured induced voltages at ohmic load with RMS current 20,8 A, terminal voltage which is calculated by using (6) and armature current. Deviation between measured and calculated induced voltage at load conditions appears due to the discretization of the generator air gap in circumferential direction with 120 points when applying analytical calculation. Analytically calculated induced voltage under load conditions is in good agreement with measurements by using (6). X_d consists of magnetizing and leakage reactance which are not separated when the induced voltage is measured at load conditions.

In the beginning of static torque characteristic calculation procedure the instantaneous currents of all three phases have to be determined. Then, the torque is calculated for different rotor positions, while the phase currents remain constant. The calculated torque characteristic for different rotor positions in dependency on these positions is static torque characteristic. Static torque characteristic according to displacement is analytically calculated by using Maxwell's stress tensor method [9] and verified by using FEM (Fig. 10).

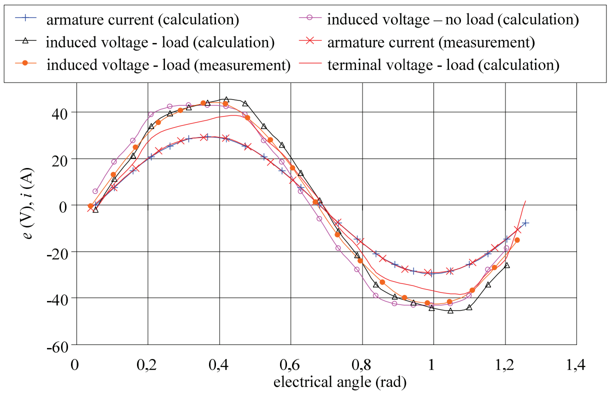

Fig.9. Comparison between instantaneous induced voltage at no-load conditions and induced voltage at 600 rpm, ohmic load and RMS current of 20,8 A

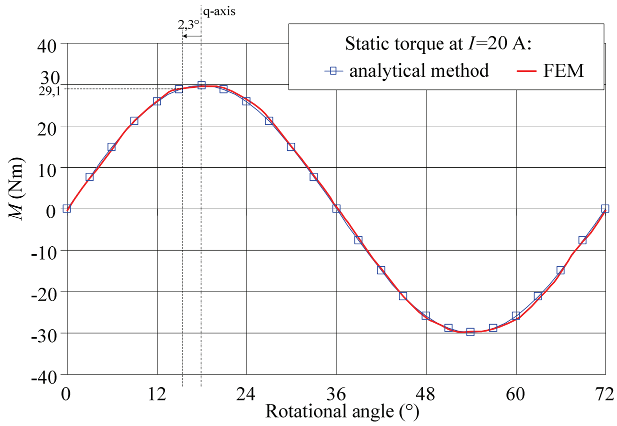

Fig.10. Static torque calculated by using FEM and analytical method in dependency on rotor displacement

Equation (5) shows that maximum torque can be achieved when the angle γ between armature current and back EMF is zero. Static torque characteristic (Fig. 10) is calculated by using RMS current 20 A and average angle γ=0,203 rad (11,5 deg), which is obtained from Fig. 8 and corresponds to mechanical angle of 2,3 deg, obtained by dividing electrical angle by the number of pole pairs. Mechanical angle can be used for determination of generator torque denoted in Fig. 10 (29,1 Nm). The result of torque measurement at RMS current 20,8 A is 29,4 Nm and the calculated torque by using (5) on the basis of Fig. 8 is 30,9 Nm.

Regarding the phasor diagram (Fig. 7) the angle φ between terminal voltage and armature current is 0,06 rad and the angle δ between terminal voltage and back EMF is 0,14 rad (Fig. 8). By changing the load size and/or load character all angles described above have to be recalculated.

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