Design Studies on a Permanent Magnet Synchronous Machine with Y- and Δ-connected Stator Winding

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Abstract – **The permanent magnet synchronous machine with an external rotor is the most important device for high performance electrical drive systems in particular for hybrid electric vehicles. The paper presents finite element analyses of a such a machine in terms of a comparison of both Y- and Δ-connected stator windings. The influence on the most important design parameters such as electromagnetic torque and phase voltages are discussed in detail.**

I. Space Vector Calculus

Starting from the stator current space vector $\underline{i}_{S,dq}$ in the dq rotor fixed reference frame and the electric angular rotor position γ, the stator currents in the $\alpha\beta$ stator fixed reference frame are generally obtained from

$$i_{S1} = i_0 + \mathrm{Re}\big(\underline{i}_{S,dq}\, e^{\jmath\gamma}\big) \ , \tag{1a}$$

$$i_{S2} = i_0 + \mathrm{Re}\big(\underline{i}_{S,dq}\, e^{\jmath\gamma}\ \mathrm{e}^{-\jmath 2\pi/3}\big) \ , \tag{1b}$$

$$i_{S3} = i_0 + \mathrm{Re}\big(\underline{i}_{S,dq}\, e^{\jmath\gamma}\ \mathrm{e}^{-\jmath 4\pi/3}\big) \ . \tag{1c}$$

With the Y-connected stator winding, any zero sequence stator current i_0 is impossible. With the Δ-connected stator winding, the unknown zero sequence current i_0 has to be determined iteratively for each angular rotor position with all operating conditions according to the vanishing sum $u_{S1} + u_{S2} + u_{S3} = 0$ of the three phase voltages.

II. Sample Analysis Results

A cogging torque as small as possible is the most important criterion for a drive system of an electric vehicle [1], [2]. Table I lists the magnitudes of the significant harmonics for load and cogging torque with various ratios b_t/τ_s of tooth width and slot pitch for both connections of the stator winding. In comparison of the Y- and Δ-connected stator windings, the latter generates a lower mean value of the load torque and simultaneously a higher cogging torque with all ratios b_t/τ_s. There is a noticeable sixth harmonic in the cogging torque only for the Δ-connected stator winding which results from the zero sequence current in the three phases. On the other hand, two design variations yield a significantly smaller 12^{th} harmonic in the cogging torque than the initial design (ID).

TABLE I
Load and Cogging Torque Harmonics (Magnitudes) with Various Ratios of Tooth Width and Slot Pitch, Y- and Δ-connected Stator Windings

Ratio	Load Torque (Nm)			Cogging Torque (Nm)	
b_t/τ_s	Average	6^{th} order	12^{th} order	6^{th} order	12^{th} order
0.257	289/281	5.3/ 6.8	3.7/ 4.6	0.0/ 9.9	7.4/ 6.6
0.300	306/298	5.6/ 6.2	1.5/ 2.0	0.0/ 8.8	4.3/ 3.6
0.343	321/312	6.4/ 6.1	2.3/ 1.9	0.0/ 7.6	0.1/ 0.6
0.386	333/323	7.5/ 6.2	4.9/ 5.2	0.0/ 6.5	4.1/ 4.5
(ID)0.429	343/332	8.9/ 6.5	5.8/ 6.5	0.0/ 5.4	6.3/ 6.6
0.471	351/339	10.5/ 7.1	4.3/ 5.3	0.0/ 4.4	5.9/ 6.2
0.514	356/343	12.2/ 8.0	1.2/ 2.3	0.0/ 3.5	3.2/ 3.4
0.557	360/345	13.8/ 9.0	2.3/ 2.1	0.0/ 2.6	0.5/ 0.6
0.600	361/346	15.2/10.2	4.7/ 5.1	0.0/ 1.8	3.8/ 4.0

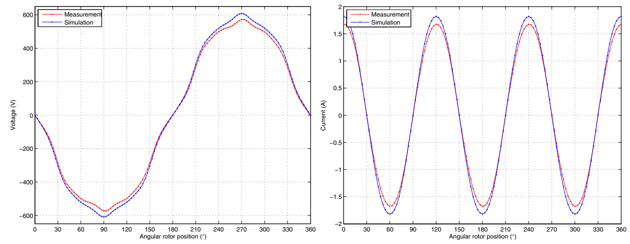

Fig. 1: No-load voltage (left) and no-load zero sequence current (right), initial design with a Δ-connected stator winding, numerical analysis and measurement results

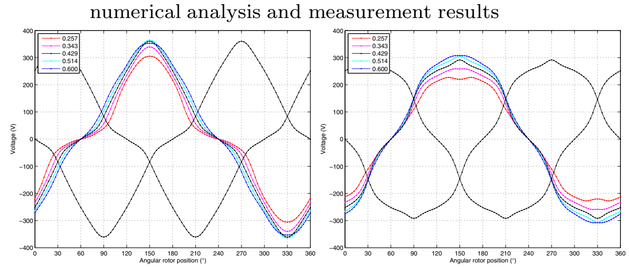

Fig. 2: No-load voltages with various ratios b_t/τ_s of tooth width and slot pitch, Y-connected (left) and Δ-connected (right) stator windings

Fig. 1 depicts no-load phase voltages and zero sequence currents of both finite element analysis and measurements for the initial design with the Δ-connected stator winding for the speed of 668 rpm. Obviously, there is a very good agreement between numerical analysis and measurement results. Fig. 2 depicts the no-load voltages of one phase with various ratios b_t/τ_s and all three phases with the initial design for the speed of 320 rpm for both connections of the stator winding. In comparison of the Y- and Δ-connected stator windings, the latter generates a smaller fundamental harmonic with all ratios b_t/τ_s. Due to the high level of saturation, the no-load voltages contain a significant third harmonic with all design variations in case of the Y-connected stator winding. On the other hand, there is no third harmonic in case of the Δ-connected stator winding which results in reduced iron losses.

References

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[2] Schmidt E., Eilenberger A.: "Calculation of Position Dependent Inductances of a Permanent Magnet Synchronous Machine with an External Rotor by using Voltage Driven Finite Element Analyses". *IEEE Transactions on Magnetics*, Vol. 45, No. 3, March 2009.

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