Asymmetry of Windings Inductance in High- Torque Low-Speed Multi-Unit Permanent Magnet Synchronous Motor

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Abstract —Aiming at Permanent Magnet Synchronous Motor (PMSM) with high-torque low-speed performance and high reliability, a multi-unit PMSM with five independent three-phase star-connected windings and five driver devices is designed. However the mutual inductances windings of the each unit are not symmetric in the original windings connection. Furthermore, the electrical torque ripple will be increased due to the asymmetric mutual inductances, when part units are operating. So an improved windings connection method is proposed in this paper. The mutual inductances of windings in the unit 1~4 become symmetric and only the mutual inductances of windings in the last one unit are asymmetric. The torque ripple is decreased using the new connection method when several units running.

I. Introduction

The high-torque low-speed PMSM can directly drive the load without speed reducer. However the superpower PMSM drivers need higher level power device which can flow lager current, the cost of the PMSM drivers will increase extremely fast. In order to solve the contradiction relation between the increasing PMSM out power and limitation of single driver out power, the multi-unit winding topology was proposed [1-2].

The topology structure of the multi-unit PMSM is shown in Fig.1.

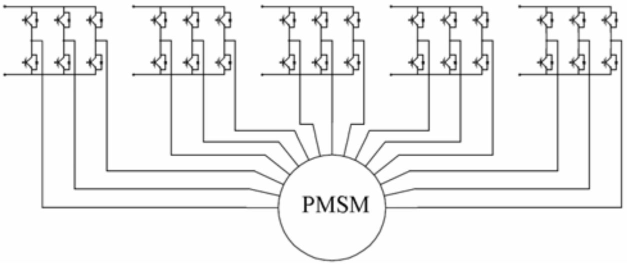

Fig. 1. Multi-unit PMSM driver system topology

The high-torque low-speed PMSM system has five driver devices and each driver is connected with independent windings. A unit includes a driver and a set of independent three-phase star-connected windings, so this motor is also called multi-unit PMSM.

There are five units in the high-torque low-speed prototype PMSM system. About 400kW is provided by each unit at the speed of 100rpm, so if all units running together, the PMSM can output 2MW. The fault tolerance and reliability are enhanced adopting the multi-unit construction. If a fault happened in one unit windings or one driver, the failure unit could be separated from the power supply, and the normal units could continue to work stably.

The Space Vector PWM (SVPWM) control algorithm is using in the five unit's parallel operation drive system. The method of water-cooling is adopted in the machine.

II. Original Windings Connection and Asymmetric Mutual Inductance

A. *Original Windings Connection*

The original windings connection is shown in Fig. 2.

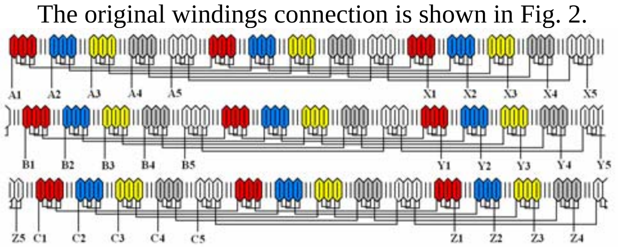

Fig. 2. Original five units' windings connection

Each unit has the three-phase star-connected windings, which can work independently and differ 120° electrical degree. Every unit windings occupy a fan-shaped region in the stator. For Example, the winding A1, B1, and C1 compose the unit 1. In Fig. 2, the different background color windings mean different units and each phase winding consists of three pole-phase groups.

B. *Asymmetric Mutual Inductance*

The basic voltage equation can be expressed as following [3-4]:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{bmatrix} + R \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} + p \begin{bmatrix} L_1 & M_{12} & M_{13} & M_{14} & M_{15} \\ M_{21} & L_1 & M_{23} & M_{24} & M_{25} \\ M_{31} & M_{32} & L_1 & M_{34} & M_{35} \\ M_{41} & M_{42} & M_{43} & L_1 & M_{45} \\ M_{51} & M_{52} & M_{53} & M_{54} & L_1 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} \quad (1)$$

Where U_i is the three-phase windings voltage of unit i (i=1, 2, 3, 4, 5), E_i is the three-phase windings EMF of unit i, I_i is the three-phase windings current of unit i, R is windings resistance matrix, p means differential operator, L_1 is inductance matrix of one unit, and M_{ij} is mutual inductance matrix between the unit i and j.

The single unit inductance matrix L_1 can be expressed as below:

$$L_1 = \begin{bmatrix} L_A & M_{AB} & M_{AC} \\ M_{AB} & L_B & M_{BC} \\ M_{AC} & M_{BC} & L_C \end{bmatrix} \quad (2)$$

Where L_A, L_B, and L_C are self inductance of three-phase windings in the same unit, M_{AB}, M_{AC} and M_{BC} are the mutual inductance of three-phase windings in the same unit.

C. *Mutual Inductance Calculation*

The no-load flux distribution is calculated by using the Finite Element Method (FEM). The local flux distribution is shown in Fig. 3.

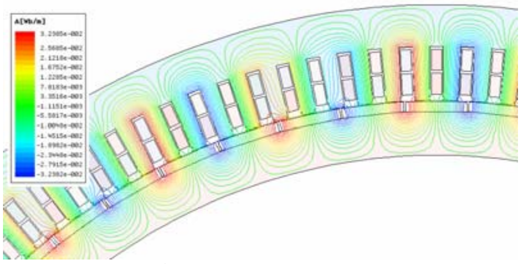

Fig. 3. Local flux distribution on no-load condition

The mutual inductance coefficient curves of unit 1 are computed using FEM. The calculation results are shown in Fig. 4.

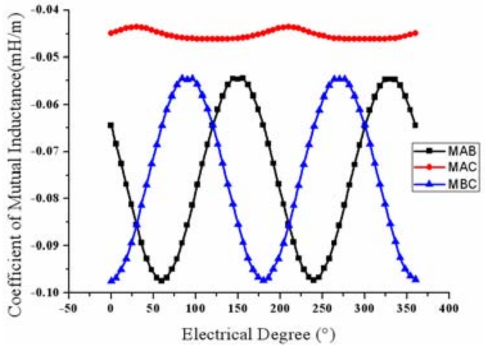

Fig. 4. Coefficient mutual inductance curves in unit 1

Fig. 4 shows that the mutual inductance coefficient M_{AC} is less than M_{AB} and M_{BC} in the unit one, and the mutual inductance coefficient value in the other unit are equal to the unit one. Furthermore, the electromagnetic torque ripple is produced owing to the asymmetric mutual inductance matrix when part units running.

III. IMPROVED WINDINGS CONNECTION AND MUTUAL INDUCTANCE

A. *Improved Windings Connection*

An improved windings connection is proposed to decrease the torque ripple due to the asymmetric mutual inductance matrix. The new windings connection is shown in the Fig. 5.

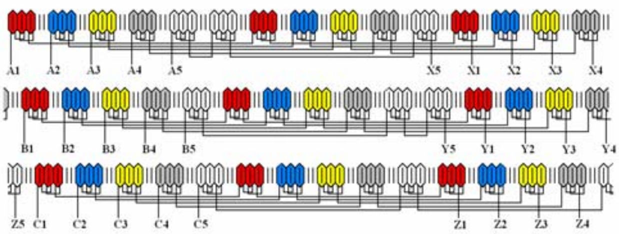

Fig. 5. Improved windings connection

The windings with same background color mean a same unit in the Fig. 5.The phase C connection in all units remains unchanged. On one hand, the second and third pole-phase groups of phase A windings shift backward one pole-phase group in the unit 1~4, and the rest pole-phase groups compose the phase A windings in the unit 5. On the other hand, the second and third pole-phase groups of phase B windings move forward one pole-phase group in the unit 1~4, and the rest pole-phase groups compose the phase B windings in the unit 5.

The mutual inductance M_{AB}, M_{BC} and M_{CA} in a unit can be expressed as following:

$$\begin{cases} M_{AB} = M_{AB1} + M_{AB2} + M_{AB3} \\ M_{BC} = M_{BC1} + M_{BC2} + M_{BC3} \\ M_{CA} = M_{CA1} + M_{CA2} + M_{CA3} \end{cases} \quad (3)$$

Where M_{AB1}, M_{BC1} and M_{CA1} mean the mutual inductance between the first pole-phase groups of three-phase, M_{AB2}, M_{BC2} and M_{CA2} mean the mutual inductance between the second pole-phase groups of three-phase, M_{AB3}, M_{BC3} and M_{CA3} mean the mutual inductance between the third pole-phase groups of three-phase.

Taking unit 1 for example, in the original connection, the M_{CA1}, M_{CA2} and M_{CA3} are less than the other mutual inductances. However the average values of M_{CA1}, M_{AB2} and M_{BC3} are less than the other mutual inductances in the improved connection. So the inductances M_{AB}, M_{BC} and M_{CA} are same average value.

B. *Mutual Inductance Calculation*

The mutual inductance coefficient curves of unit 1 are computed using FEM. The calculation results are shown in Fig. 6.

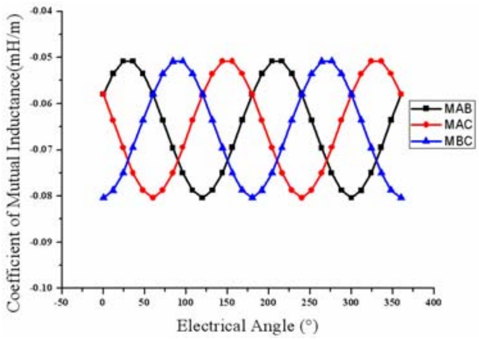

Fig. 6. Coefficient mutual inductance curves in unit 1

The Fig.6 shows that the values of mutual inductance coefficients of three-phase windings are equal in the unit 1~4.

However, the mutual inductances of unit 5 aren't equal by using the improved windings connection.

IV. REFERENCES

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