Mon-Af-Po1.04-24 [54] A Synthetic Frozen Permeability Method for Torque Separation in Hybrid PM Variable-Flux Machines

Author: Meng Ge, Jian Li, Ronghai Qu, Yang Lu, Junhua Chen

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, 430074, China

Abstract

In **hybrid permanent magnet variable flux machine** (HPM-VFM), both high coercive force magnet, e.g. NdFeB, and low coercive force magnet, e.g. Alnico are employed. The variable flux is achieved due to Alnico while the torque density is boosted thanks to NdFeB, thus, a wide speed range and high efficiency can be obtained.

In HPM-VFM, The dimensions of the two types of PMs not only determine the output capacity, but also influence the magnetization performance of HPM-VFM. For the design and optimization, the total torque segregation and the PM torque segregation of the two kinds of PMs are needed to examine the actual contribution of them.

Generally, **frozen permeability method** (FPM) can separate on-load field components produced by various excitation sources. However, in variable-flux machine, due to the **nonlinear magnetic properties** of Alnico, the operating point of Alnico changes along with the variation of the load conditions, as a result, conventional FPM (CFPM) will cause an obvious error in on-load PM field components. In the proposed method, the **recoil line** of Alnico is considered and frozen in the finite element analysis (FEA), then the total PM torque and individual PM torques produced by different magnets can be obtained considering **cross coupling effects**. Finally, the results based on the two methods are compared with the value calculated by direct nonlinear FEA.

The Referenced HPM-VFM

The Principle of VFM

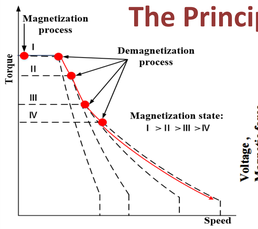


Fig. 1 Principle for extending the torque-speed range.

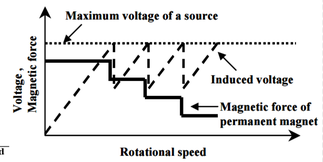


Fig. 2. Voltage regulation at variable-speed in variable flux machine.

The PMs are magnetized to high state at low speed region and demagnetized correspondingly along with the increase of the speed.

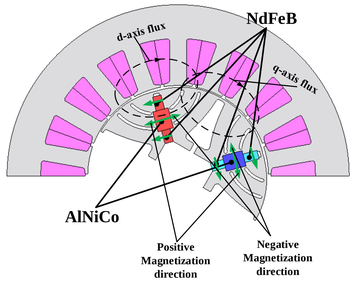


Fig. 3 The topology of the referenced HPM-VFM.

Machine Topology

TABLE I
MAIN DIMENSIONS AND PARAMETERS OF THE REFERENCED HPM-VFM

Parameter	Value	Parameter	Value
Rated power	1.4 kW	Rated current	11 A
Rated speed	2000 rpm	Stator slots	18
Stator outer diameter	142 mm	Rotor poles	4
Stator inner diameter	75 mm	B_r (NdFeB)	1.3 T
Rotor outer diameter	74 mm	H_c (NdFeB)	910 kA/m
Stack length	50 mm	B_r (Alnico)	1.089 T
PM whole length	20 mm	H_c (Alnico)	133 kA/m

- ◆ Both Alnico and NdFeB are tangentially magnetized.
- ◆ The magnetization state and direction of NdFeB are constant, while that of Alnico can be adjusted.
- ◆ To avoid negative d-axis current demagnetizing the Alnico, q-axis flux barriers are set to achieve reverse saliency ratio with $L_d > L_q$.

Basic Principle and Frozen Permeability Method

Operating Process

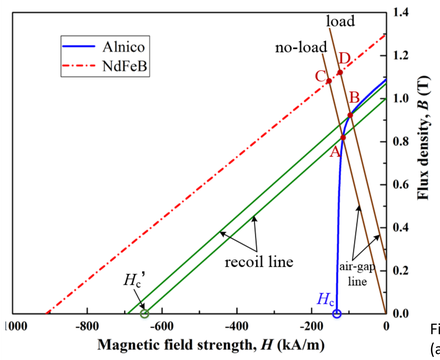


Fig. 4 B-H curve of the employed Alnico and NdFeB.

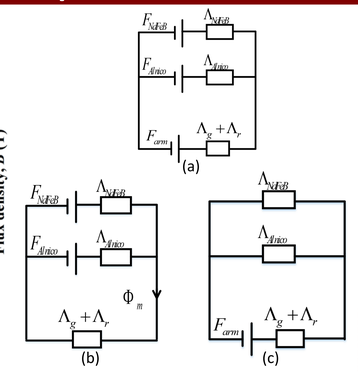
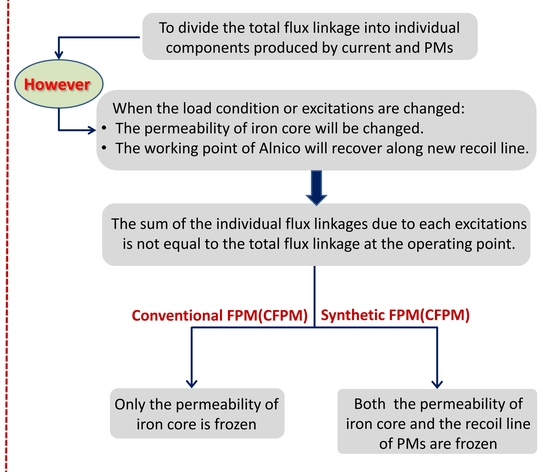


Fig. 5 Magnetic circuit model of HPM-VFM in FPM: (a)all excitation (b) PM single excitation (c) current single excitation.

- ◆ The B-H curve of NdFeB is linear, thus its working point only moves along the demagnetization curve.
- ◆ The working point of Alnico recovers along the corresponding recoil line and reach a resultant coercive force H_c'. As a result, H_c' for each working point in Alnico is different.
- ◆ $F_{Alnico} = H'_{c\_Alnico} t_{Alnico}$. The equivalent magneto-motive force (MMF) for Alnico will be changed with the variation of the excitations, consequently, the PM flux linkage calculated by CFPM will cause an error.

Two Frozen Permeability Methods



The Synthetic Frozen Permeability Method in FEA

- Both in **fully magnetized state** and **incompletely magnetized state**, the results calculated by CFPM and SFPM are compared.
- The sums of the individual flux linkages using CFPM and SFPM are compared with the total flux linkage calculated by nonlinear FEA.

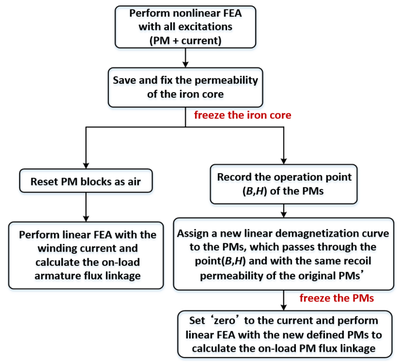


Fig. 6 Flow chart for the SFPM in FEA

- ◆ Both in two magnetization states, the value of the on-load PM flux linkage calculated by CFPM is lower.
- ◆ The error caused by two CFPM is larger in incompletely magnetized state.

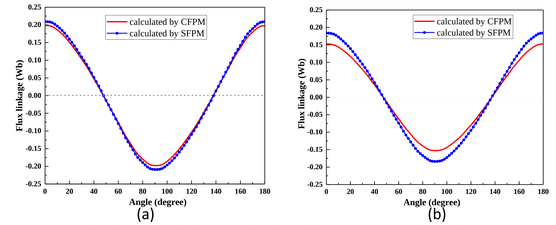


Fig. 7 On-load PM flux linkages calculated by two FEMs and nonlinear FEA in: (a) fully magnetized state (b) incompletely magnetized state.

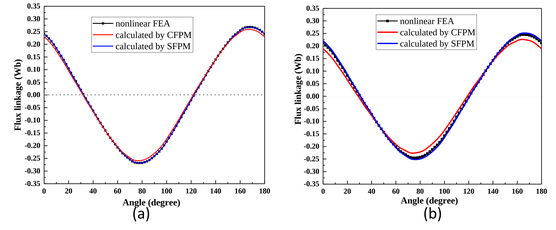


Fig. 8 Sum of the individual flux linkages calculated by two FEMs and the total flux linkages calculated by nonlinear FEA in:(a) fully magnetized state (b) incompletely magnetized state.

Torque Decomposition

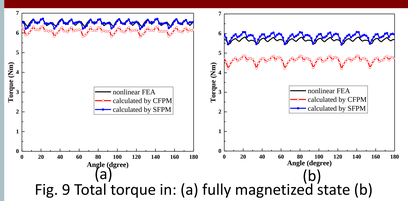


Fig. 9 Total torque in: (a) fully magnetized state (b) incompletely magnetized state.

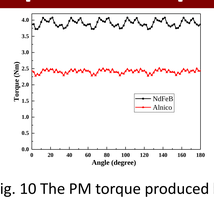


Fig. 10 The PM torque produced by the NdFeB and Alnico with SFPM.

- D_{value} is the error between the sum of the decomposed torques by the two FPMs and the total torque calculated by nonlinear FEA.
- The PM torque T_{PM} is obtained through the on-load PM field calculation by applying q-axis current only.
- ◆ The results of the separated torque components calculated by SFPM match well with that of nonlinear FEA.
- ◆ The exact contribution of the two PMs can be seen in Fig. 10, and further optimization of the PMs' dimension will be carried out based on the proportion of the two individual PM torques.

TABLE II
COMPARISON OF THE AVERAGE TORQUES CALCULATED BY TWO FPMS AND NONLINEAR FEA IN FULLY MAGNETIZED STATE

Items	CFPM	SFPM	Nonlinear FEA
$T_{PM}(Nm)$	5.88	6.28	-
$T_{Rel}(Nm)$	0.22	0.22	-
$T_{total}(Nm)$	6.10	6.50	6.52
$D_{value}(\%)$	6.44	0.31	-

TABLE III
COMPARISON OF THE AVERAGE TORQUES CALCULATED BY TWO FPMS AND NONLINEAR FEA IN INCOMPLETELY MAGNETIZED STATE

Items	CFPM	SFPM	Nonlinear FEA
$T_{PM}(Nm)$	4.34	5.55	-
$T_{Rel}(Nm)$	0.30	0.30	-
$T_{total}(Nm)$	4.64	5.85	5.66
$D_{value}(\%)$	18.02	3.36	-

Conclusion

- ❖ This paper proposes a synthetic frozen permeability method in order to accurately separate the on-load PM field components in the HPM-VFM which is designed with nonlinear permanent magnets. Both the permeability of the iron core and recoil line of the PMs are frozen in the proposed method.
- ❖ The results calculated by SFPM coincide well with the nonlinear FEA, and it is more accurate and reliable than CFPM.
- ❖ The PM torque components due to the two types of PM can be separated with SFPM considering cross coupling effect, which provides valuable insights for further design and optimization in HPM-VFM.

Presented at the MT25 Conference, 2017 Aug. 27 – Sept. 1, Netherland, Amsterdam; Session: Mon-Af-Po1.04 [54]; ID Number: 1095 Poster: Ms. Meng Ge.