Sensors & Transducers

http://www.sensorsportal.com

Study on Permanent Magnet Synchronous Demagnetization Fault Performance

[1, 2] Zhiyan ZHANG, [1] Hongzhong MA, [2] Cunxiang YANG, [3] Duanlei YUAN

[1] College of Energy and Electrical Engineering, Hohai University,
Fucheng West Road No. 8 Nanjing City Jiangsu Province, 210098, China
[2] College of Electrical Information Engineering, Zhengzhou University of Light Industry,
Dongfeng Road No. 5 Zhengzhou City Henan Province, Zhengzhou 450002, China
[3] Ministry of Science and Technology State Grid Pinggao Group Co. Ltd.,
Nanhuan East Road No. 22 Pingdingshan Henan, 467001, China
[1] Tel.: 15039072321, fax: 037163556790
E-mail: 541046459@qq.com

Received: 18 April 2014 /Accepted: 30 May 2014 /Published: 30 June 2014

Abstract: The relationship of permanent magnetic material characteristic parameters was analyzed, and a simulation method of a permanent magnet synchronous motor (PMSM) rotor demagnetization fault was put forward. Based on this, a simulation model of the PMSM under partial demagnetization and uniform demagnetization fault were established, and different degrees demagnetization fault was simulated. Relationship between output torque and initial phase was gained by applying different initial angle current excitation source in order to establish the reasonable simulation model. Simulation results show that magnetic field strength and output torque get smaller and smaller with increasingly fault severity. The magnetic field asymmetry of PMSM partial demagnetization is more and more serious with increasingly fault severity, and the magnetic field scale of PMSM uniform demagnetization decreased significantly. The harmonic analyses using Fast Fourier Transform (FFT) show that the fault diagnosis method based on the harmonic wave analysis is only suitable for partial demagnetization fault of the PMSM, and not apply to uniform demagnetization fault of the PMSM.

Keywords: PMSM, Demagnetization, Fault, Simulation.

1. Introduction

Permanent magnet motor with high power density and high efficiency is the best choice of electric vehicle driving motor. PMSM the same as conventional motor when they long-term run will be possible to appear fault, such as bearing fault, eccentricity fault, etc., which seriously affect the safety and reliability of motor operation. And because permanent magnets are embedded in permanent magnet motor rotor, the permanent magnet demagnetization fault is the special fault type. The main reason of the permanent magnet demagnetization is the armature reaction induced by high temperature and large current, especially the armature reaction under the big torque condition, and big current by the short circuit current of the inverter and the stator winding faults, and overload current. PMSM stator winding inter turn short circuit fault will cause short circuit current increasing and the temperature rising, which causes the PMSM unbalanced operation, if the further development of

http://www.sensorsportal.com/HTML/DIGEST/P_2152.htm

fault, the motor will be the serious fault including the inter phase short circuit fault and phase to ground fault [1]. These faults, overload operation and instantaneous overload operation will produce large current higher than the rated current for several times, and large current will produce very big reverse magneto-motive force which will have strong demagnetization to permanent magnets increasing the demagnetization probability. Magnetic domain of permanent magnet will move under high temperature, which makes them rearrange their location in the direction of stability, and the magnetic field offset each other, so that the permanent magnet is not display magnetic to external, namely occurrence demagnetization phenomenon. There are two main reasons of high temperature demagnetization. On the one hand, eddy current loss affected tooth harmonic results in higher temperature increase under the PMSM normal operation; On the other hand, in order to meet the performance requirements PMSM structure design require high close degree, high energy permanent magnets and large winding fill factor in some special occasions, but these design requirements is not conducive to dissipate the heat and the PMSM running environment cooling conditions, which will result in the permanent magnet operating point temperature is further increased, increasing the permanent magnet demagnetization fault possible. In order to meet the load demand under PMSM demagnetization fault operation, there is need to increase the stator current producing the larger opposite magnetic potential and making the PMSM temperature further rise, which form a vicious spiral. At last, the permanent magnets operate below the working point of magnetic so that there are produce irreversible demagnetization. In addition, the defect of permanent magnet material itself, such as the easily corroded Nd-Fe-B and the PMSM high-speed operation will make permanent magnet spalling and resulting in demagnetization. On the other hand, sintered rare earth permanent magnet is very fragile, so that there is likely to produce partial demagnetization during the production, transport and operation.

At present, the object of research on motor fault diagnosis are mainly traditional large motor, such as asynchronous motor stator fault [2, 3] and rotor fault [4-7], and synchronous motor winding fault [8, 9] and rotor fault [10, 11]. Research on PMSM fault diagnosis at home and abroad is relatively less, and the main study is in abroad. Demagnetization of PMSM will generate specific harmonic in the stator current [12, 13]. There are different diagnosis method based on different signal analysis method of the stator current, and diagnostic methods mainly include Hilbert-Huang transform (HHT) [14], Continuous Wavelet transform (CWT) [15], Discrete Wavelet transform (DWT) [15], Fast Fourier Transformation (FFT) [16]. In addition, there are another method of equivalent network [17, 18], which use air-gap permeance network as permanent magnet equivalent of permanent magnet synchronous motor in order to on-line diagnosis of permanent magnet demagnetization fault through measurement of the flux.

The PMSM rotor demagnetization were studied in the paper taking Prius hybrid vehicle interior PMSM of the Toyota as an example. After the demagnetization fault realization method was studied, the partial and uniform demagnetization simulation model was established. The performance of the PMSM demagnetization fault under no-load and load conditions were obtained by analyzing the electromagnetic parameters and performance curve after demagnetization fault. Some meaningful conclusions provide a strong basis for fault diagnosis of the demagnetization.

2. Characteristics Quantity Selection of PMSM Demagnetization Fault

According to the literature [15], the special frequency signal of the stator current will be generated after PMSM rotor demagnetization fault, and the relationship between the fault frequency and power frequency can be expressed the flowing,

$$f_{dmg} = f_s(1 \pm \frac{k}{p}), \tag{1}$$

where $f_{\deg}$ is the fault frequency, f_s is the power frequency, k is the integer, 1, 2,... and p is the poles pair of PMSM.

Type (1) can also be expressed as,

$$f_{dmg} = f_s(pk \pm 1), \tag{2}$$

So we can sample the stator current signal and acquire the stator current spectrum using signal transformation method to analyze of its harmonic components, then diagnose the rotor demagnetization occurrence and judge the severity degree of demagnetization. In fact, uniform demagnetization fault is not appearing the new harmonic, even if partial demagnetization is likely to produce the same fault harmonic because of the influence of environmental noise or measuring equipments. So that the new harmonic appearing is not as the fault diagnosis characteristics quantity, but the size of harmonic can be regard as partial demagnetization fault diagnosis basis.

3. PMSM Simulation Model Establishment under Normal and Demagnetization Condition

3.1. Simulation Model Establishment

Finite element (FEM) analysis method is a numerical analysis method, which can be used to analyze various characteristics under static, transient, steady state, normal condition and fault condition of electromagnetic device, such as motor, transformer, and so on, because the method can reflect the influence of motor internal factor and establish the most accurate motor model. In this paper, based on Ansoft software platform, simulation model for the PMSM of Prius hybrid vehicle is established, Permanent magnet type is N36-Z20 and interior V distribution, and power supply is the inverter power supply, and the stator winding is a single-layer coil structure. Rated power, speed and voltage are 50 kW, 3000 rpm and 380 V respectively. Number of pole pairs and stator slots is 4 pairs and 48 slots. According to the motor structure symmetry and the simplification model principle of FEM analysis method, a pair of magnetic poles is modeled as shown in Fig. 1.

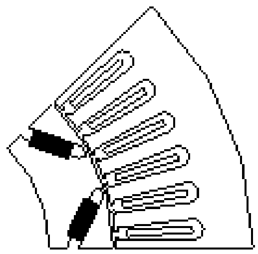


Fig. 1. 1/8 PMSM simulation mode.

3.2. Demagnetization Fault Simulation Method

If the direction of external magnetic field strength H is reversed, at the demagnetization curve of the permanent magnetic materials under the coordinate system, the magnetic induction intensity can be expressed as,

$$B = -\mu_0 H + \mu_0 M_p, \tag{3}$$

where μ_0 is the vacuum relative magnetic permeability, H is the external magnetic field strength and M_p is the polarization intensity.

Permanent magnet performance is usually expressed by four parameters, namely the relative permeability μ_r (expressed M_μ in Ansoft software), the coercivity H_c, residual magnetic induction intensity B_r and polarization intensity M_p. Residual magnetic induction intensity B_r refers to magnetic induction intensity when the magnetic field intensity H is zero. The relationship between the polarization M_p and residual magnetic induction intensity B_r can be derived as shown in formula (4).

$$M_p = B_r / \mu_0, \tag{4}$$

The permanent magnetic material coercivity H_c refers to the size of H when magnetic induction intensity B is not zero. Working point of permanent magnet above the hysteresis loop, the demagnetization curve is linear, and then the relationship between the magnetic field strength B, residual magnetic induction intensity Br and the relative permeability μ of the three can be expressed as,

$$B = B_r - \frac{B_r}{H_c} H = B_r - \mu H, \tag{5}$$

$$\mu = \mu_0 \mu_r = \frac{B_r}{H_c}, \tag{6}$$

Obviously, type (4) cannot be used as a basis for analysis of demagnetization fault. Formula (7) can be by formula (3) and (4).

$$B = -\mu_0 H_c + B_r, \tag{7}$$

According to determine the working point under normal operating conditions and type (5), the four parameter of type (7) can be obtained. If all the permanent magnets occur uniform demagnetization fault, magnetic induction intensity B become the original 75 %, namely 25 % demagnetization, denoted as B_{dmg}, then $B_{dmg} / B = 0.75$, this can be expressed as,

$$\frac{B_{dmg}}{B} = \frac{-\mu_0 H_{cdmg} + B_{rdmg}}{-\mu_0 H_c + B_r}, \tag{8}$$

where subscript dmg is the fault parameter.

Therefore demagnetization simulation realization is only change the size of Br is not appropriate according to the B_r definition. Based on Ansoft software platform, the permanent magnet synchronous motor with different degree of demagnetization fault simulation can be changed by permanent magnetic material parameters of H_c and B_r.

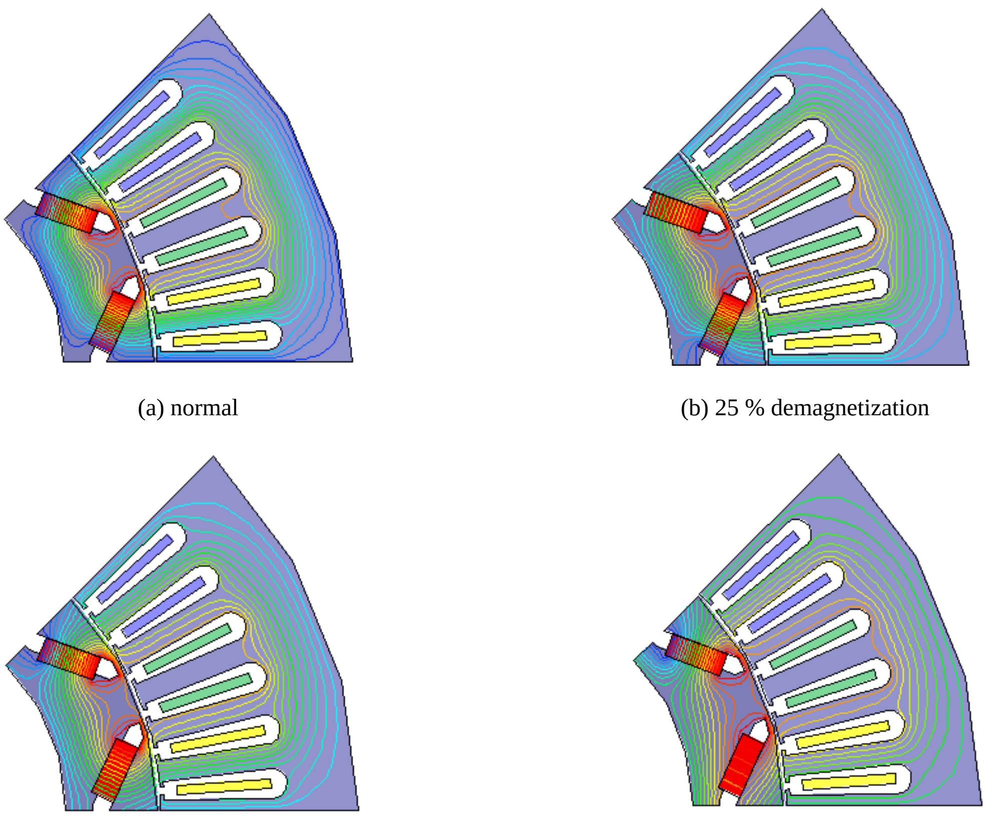
4. Analysis of the PMSM Partial Demagnetization Fault Performance

PMSM demagnetization fault can be divided into two kinds. One is entire permanent magnet poles occurrence uniform demagnetization to a certain extent, which is called whole demagnetization or uniform demagnetization, and two is partial permanent magnet poles occurrence demagnetization to a certain extent, which is called partial demagnetization or local partial. Permanent magnet demagnetization fault is usually whole permanent magnet poles demagnetization called uniform magnetic, because the symmetry magnetic circuits result in demagnetization magnet-motive force (MMF) of the stator current action on all of the permanent magnets.

4.1. Analysis of Performance under No-load

If the one magnet in 1/8 simulation model occurs demagnetization, according to the above realization method of demagnetization fault simulation, permanent magnet parameters are modified to realize the three degrees demagnetization fault simulations occurred in 25 %, 50 % and 75 % under no-load steady-state. The magnetic field strengths are shown in Fig. 2.

In Fig. 2, there are the maximum values of the magnetic field strength of normal, 25 % demagnetization, 50 % demagnetization and 75 % demagnetization are 1.7294e-002 wb/m, 1.4071e-002 wb/m, 1.1951e-2 wb/m and 9.8304e-3 wb/m respectively. At the same time, the magnetic field strength is more and more weak and the magnetic field in homogeneity is more and more serious along with the augment of demagnetization fault severity.



(a) normal

(b) 25 % demagnetization

(c) 50 % demagnetization

(d) 75 % demagnetization

Fig. 2. Flux lines of the rotor normal and different degrees demagnetization under no-load steady state conditions.

4.2. Influence of Simulation Parameters and PMSM Output under Transient Condition

The motor parameters are analyzed to determine the best motor structure and obtain the best motor performance.

Three-phase sinusoidal symmetrical current is applied through the stator windings when transient is simulated. In order to make noticeable simulation effect, the load current peak is 400 A and phase sequence is A+C-B+, and the length of simulation time is 10 ms. The PMSM output torque is different if the PMSM is applied current source excitation of different power angle. In order to obtain the maximum output torque and optimize the initial parameters of the simulation, making the efficiency of the PMSM achieve optimal and output power reach the maximum under the same condition, the paper simulate the power angle parameters between 0 and 60 degrees of current source excitation, and the simulation results are shown as Fig. 3.

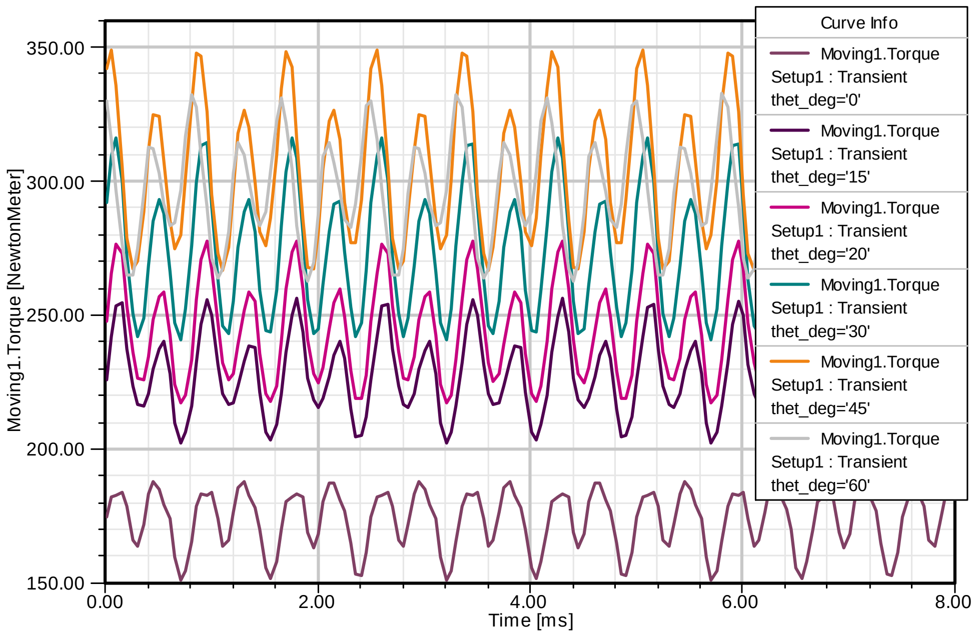
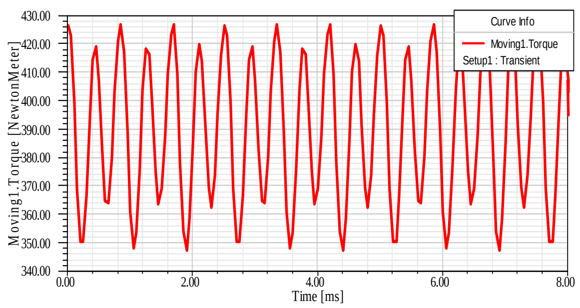


Fig. 3. The relationship between output torque and time under different initial power angle.

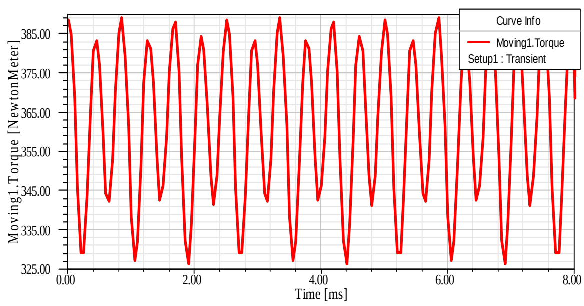
As is shown in Fig. 3, 45 degrees of the initial phase angle is a turning point of the motor output torque, so the angle of 45 degrees is the point of the motor output torque maximum torque. Dynamic simulation is implemented in normal, 25 % demagnetization, 50 % demagnetization and 75 % demagnetization of a pole pairs respectively when power angle is 45 degrees.

The size of the PMSM output torque in the simulation is as shown in Fig. 4.

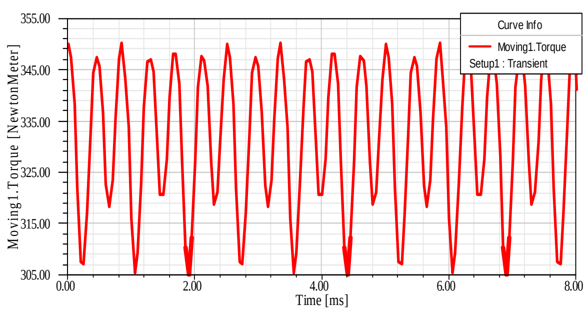
In Fig. 4, there are the PMSM output torqueses decreasing along with demagnetization degree increasing in partial demagnetization. The PMSM output torque is respectively 387.5 NM, 357.7 NM, 327.44 NM and 298.1 NM under at normal working, single pole occurrence 25 % demagnetization, 50 % demagnetization, and 75 % demagnetization. Moreover, the output torque is reduced to about 23 % of normal output torque when a single pole reached 75 % demagnetization.



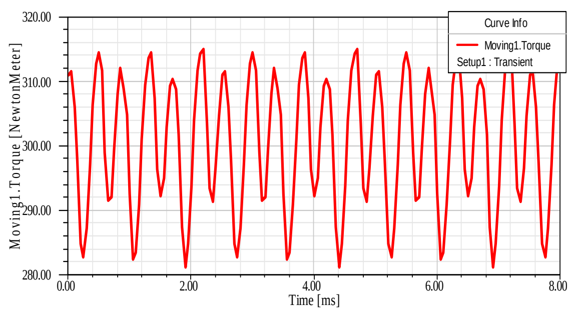
(a) normal



(b) 25 % demagnetization



(c) 50% demagnetization



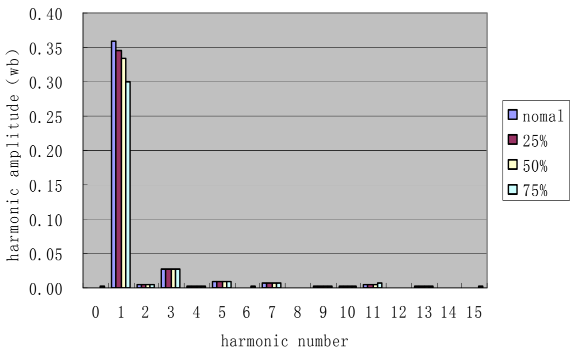
(d) 75% demagnetization

Fig. 4. Output torque of the rotor normal and different demagnetization under load transient state conditions.

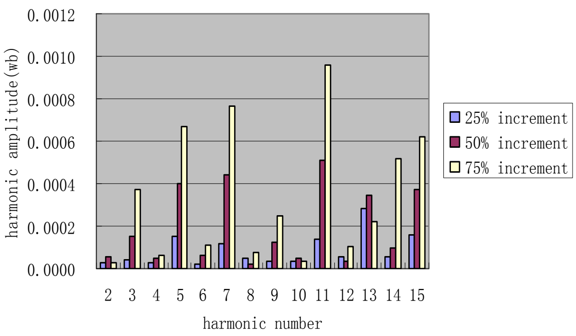
4.3. Partial Demagnetization Fault Harmonic Analysis

The PMSM flux signal under the normal state is analyzed by FFT method. The analysis time is a cycle, namely the fundamental frequency is 200 Hz, and the harmonic component size is as shown in Fig. 7.

For better comparison of the harmonic component size and acquisition the most characteristic quantity sensitive in normal, 25 % demagnetization, 50 % demagnetization and 75 % demagnetization, the harmonic components of four cases is analyzed and can be expressed as shown in Fig. 5.



(a) harmonic size



(b) harmonic increment

Fig. 5. Flux linkage harmonic analysis using FFT of the rotor different conditions.

In Fig. 5, when the rotor of the PMSM occur demagnetization fault the flux linkage fundamental wave amplitude significantly reduces relative to the rotor normal condition, and with the increase of rotor demagnetization degree the fundamental wave amplitude gets smaller and smaller. In Fig. 5(b), even harmonic amplitude is very small, and the harmonic amplitude of variation is not obvious with the demagnetization degree severity. But the odd harmonic amplitude is obviously increased with the demagnetization degree severity. It is worthwhile to note that 9 times and 13 times harmonic amplitude changes is relatively is not very clear, so they should not be selected as the fault feature to diagnose fault occurrence.

5. Performance Analysis of the PMSM Uniform Demagnetization

5.1. Flux Linkage Analysis under Transient Condition

Applying the sinusoidal AC voltage source, setting the resistance and reactance parameters, a simulation model was established. The simulation flux linkage waveform under the permanent magnet of normal, 25 % uniform demagnetization, 50 % uniform demagnetization and 75 % uniform demagnetization at the speed of 3000 rmp are shown in Fig. 6.

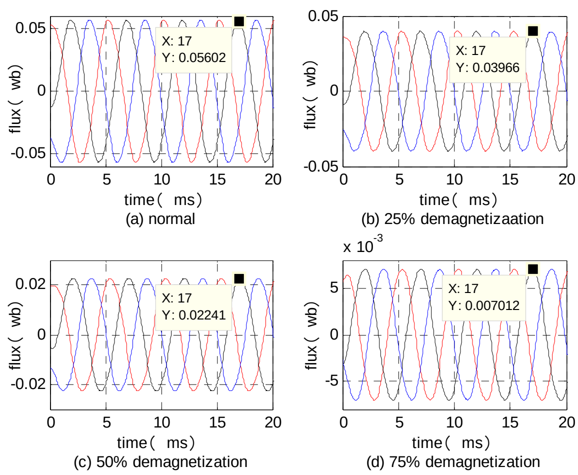


Fig. 6. Flux linkage under various load operation conditions.

The stator flux waveforms are sinusoidal waveform and the amplitudes are 0.056 wb, 0.040 wb, 0.022 wb and 0.007 wb respectively in Fig. 6 under normal, 25 % demagnetization, 50 % demagnetization and 75 % demagnetization of the PMSM, which with the severity of fault increase is decreased significantly, but not proportional relationship. Because the stator winding flux linkage equation can be expressed as,

$$\begin{bmatrix}\Psi_A\\ \Psi_B\\ \Psi_C\end{bmatrix}=\begin{bmatrix}L_{AA} & M_{AA} & M_{AC}\\ M_{BA} & L_{BB} & M_{BC}\\ M_{CA} & M_{CB} & L_{CC}\end{bmatrix}\begin{bmatrix}i_A\\ i_B\\ i_C\end{bmatrix}+\begin{bmatrix}\Psi_{fA}\\ \Psi_{fB}\\ \Psi_{fC}\end{bmatrix}, \quad (10)$$

where M_{AB}, M_{BC} and M_{AC} are the mutual inductance between three-phase winding, L_{AA}, L_{BB} and L_{CC} are the self inductance of three-phase winding, Ψ_{fA}, Ψ_{fB} and Ψ_{fC} are the three phase winding flux by the permanent magnet excitation.

The equation (10) shows that the first item produced by the stator winding of the three-phase current applying the same excitation is equal under the normal and demagnetization fault operation of the motor condition, but the second item is produced by permanent magnet is decreased in proportion to demagnetization degree. So the total flux is not in proportion to the change of demagnetization degree.

5.2. Flux Linkage Harmonic Analysis

Arbitrary data of a phase in Fig. 6 for harmonic analysis, the results are shown in Fig. 7.

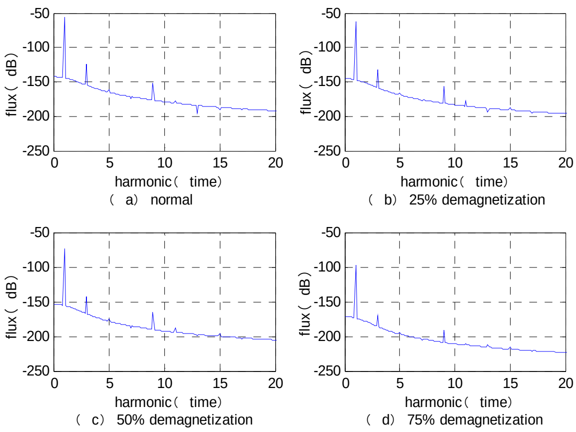


Fig. 7. Harmonic chart of flux under various operation conditions of the PMSM.

In Fig. 6 and Fig. 7, the PMSM time-domain waveform and harmonic analysis waveform during normal operation, the model of the motor is ideal, and the flux is basic conform to the change rule of sine waveform. Fig. 7 vertical coordinate is dB (20log), and under normal operation, 25 %, 50 % and 75 % demagnetization operation conditions, fundamental wave amplitude gradually decreases, and the 3 and 9 harmonics relative value with the severity of fault is gradually reduced, and no new harmonic components occur, thus the current and back EMF harmonics composition analysis does not have obvious results to demagnetization fault. Based on this, the harmonic analysis method is invalid to diagnose a PMSM uniform demagnetization fault.

5.3. Torque Analysis

The uniform demagnetization torque under various working conditions research results show that the output torque of the PMSM is respectively 387.5 NM, 191.2 NM, 70.5 NM and 20.8 NM under normal operation, 25 %, 50 % and 75 % uniform demagnetization operation. Therefore the output torque is obviously decreased along with the increase of demagnetization degree. While all poles demagnetization rate reached 75 %, the output torque is reduced to about 5 % of the normal output torque.

6. Conclusions

Partial and uniform demagnetization fault of the PMSM in varying degrees under no-load and load state are simulated using FEM analysis software in this paper, and the simulation results show that the reasonable demagnetization fault waveform can be obtained by changing the permanent magnet material parameters. And initial phase of excitation source has great effect on the output torque of PMSM, when initial phase angle is 45 degrees, the PMSM motor performance is the best and output torque arrives maximum. And the results of partial demagnetization and uniform demagnetization simulations show that the magnetic field strength and the output torque will be reduced with the increase of demagnetization fault severity, but the uniform demagnetization of the PMSM will be significantly decreased than the partial demagnetization. The harmonic analysis show that the 3 times, 5 times, 7 times, 11 times and 15 times harmonic amplitude is increased significantly under the partial demagnetization fault condition, hence they can be selected as the fault feature to diagnose fault occurrence. But the 3 and 9 harmonics relative value increased with the severity of fault is gradually reduced under the uniform demagnetization of the PMSM, and no new harmonic components appear. Therefore, the harmonic wave analysis method is not suitable to diagnosis of uniform demagnetization fault occurrence and severity. The conclusions in the paper provide the basis for the demagnetization diagnosis.

Acknowledgements

We express our gratitude to the development of automobile industry of Shanghai Science and Technology Fund Foundation (Grant No. 1106), because they provide research funding. The PMSM and part experimental equipment of the research was performed with the support from new energy automotive business department SAIC Motor for which we express our gratitude.

References

[1]. Li Liu, David A Cartes, On-line identification and robust fault diagnosis for nonlinear PMSM drives diagnosis for nonlinear PMSM drives, in *Proceedings of the American Control Conference (ACC'05)*, Portland, United States, 8-10 June 2005, pp. 2023–2027.

[2]. Rangarajan M. Tallam, Thomas G. Habetler, Ronald G. Harley, Self commissioning training algorithms for neural networks with applications to electric machine fault diagnostics, *IEEE Transaction on Power Electronics*, Vol. 17, Issue 6, 2002, pp. 1089-1095.

[3]. Wang Xuhong, He Yigang, Inter turn fault detection of asynchronous motor stator winding based on diagonal recurrent neural network, *Electric Power*

Automation Equipment, Vol. 29, Issue 7, 2009, pp. 60-63.
[4]. Ma Hongzhong, Hu Qiansheng, Huang Yunkai, et al, Simulating and experiment studying on rotor winding fault of induction motor, *Proceedings of the CSEE*, Vol. 23, Issue 4, 2003, pp. 107-112.
[5]. Hou Xinguo, Wu Zhengguo, Xia Li, A method for detecting rotor faults in induction motors based on the square of the park's vector modulus, *Proceedings of the CSEE*, Vol. 23, Issue 9, 2003, pp. 137-140.
[6]. Liu Zhenxing, Yin Xianggen, Zhang Zhe, et al, On-line monitoring and diagnosis way based on spectrum analysis of Hilbert modulus in induction motors, *Proceedings of the CSEE*, Vol. 23, Issue 7, 2003, pp. 158-161.
[7]. Fang Fang, Yang Shi-Yuan, Hou Xin-Guo, Rotor fault feature extraction of motor faults of induction motor based on a modified music method, *Proceedings of the CSEE*, Vol. 27, Issue 30, 2007, pp. 72-76.
[8]. Xia Chang-Liang, Fang Hong-Wei, Jin Xue-Feng, et al, Numerical analysis of stator winding faults in synchronous generator, *Proceedings of the CSEE*, Vol. 26, Issue 10, 2006, pp. 124-129.
[9]. Hao Liangliang, Sun Yuguang, Qiu Arui, et al, Fault location and short circuit turns estimation of inter-turn short circuits of field windings in non-salient-pole synchronous generator, *Proceedings of the CSEE*, Vol. 31, Issue 21, 2011, pp. 85-91.
[10]. Wang Xiangheng, Chen Songlin, Wang Weijian, et al, A study of armature winding internal faults for turbo-generators, *IEEE Transactions on Industry Applications*, Vol. 38, Issue 3, 2002, pp. 625-631.
[11]. J. A. Rosero, J. Cusido, A. Garcia, et al, Broken bearings and eccentricity fault detection for a permanent magnet synchronous motor, in *Proceedings of the 32nd IEEE Annual Conference on Industrial Electronics. IECON'06*, Paris, France, 6-10 November, 2006, pp. 964-969.
[12]. W. Le Roux, R. G. Harley, T. G. Habetler, Detecting rotor faults in permanent magnet synchronous machines, *IEEE Transactions on Power Electronics*, Vol. 22, Issue 1, 2007, pp. 322-328.
[13]. W. Le Roux, R. G. Harley, T. G. Habetler, Converter control effects on condition monitoring of rotor faults in permanent magnet synchronous machines, in *Proceedings of the 38th IAS Annual Meeting, Conference record of the IEEE Industry Applications Conference*, Salt Lake City, United States, 12-16 October 2003, Vol. 2, pp. 1389-1396.
[14]. Song Bo-Ban, Cui Jian-Guo, Liu Dong, Diagnosis of motor by means of Hilbert-Huang transform and simulation technology, *Journal of Shenyang Institute of Aeronautical Engineering*, Vol. 27, Issue 4, 2010, pp. 79-82.
[15]. Jordi-Roger Riba Ruiz, Javier A. Rosero, Antonio Garcia Espinosa, et al, Detection of demagnetization faults in permanent-magnet synchronous motors under nonstationary conditions, *IEEE Transactions on Magnetics*, Vol. 45, Issue 7, 2009, pp. 2961-2969.
[16]. J. Rosero, J. Cusido, A. Garcia, J. A. Ortega, et al, Study on the permanent magnet demagnetization fault in permanent magnet synchronous machines, in *Proceedings of the 32nd Annual Conference of the IEEE Industrial Electronics Society (IECON'06)*, Paris, France, 6-10 November, pp. 879-884.
[17]. Yin Hua-Jie, He Yun, Modeling of permanent magnet for PM motor, *Micromotors*, Vol. 37, Issue 6, 2004, pp. 14-18.
[18]. Zhou Jie, Xie Wei, Wang Guoliang, Application and comparison of finite element method and equivalent magnetic network method in computing electromagnetic parameters of permanent-magnet motor, *Journal of Xi'an Jiaotong University*, Vol. 32, Issue 4, 1998, pp. 23-26.