CHEMICAL ENGINEERING TRANSACTIONS
VOL. 46, 2015

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Peiyu Ren, Yancang Li, Huiping Song

ISBN 978-88-95608-37-2; **ISSN** 2283-9216

DOI: 10.3303/CET1546173

Affect on Permanent Magnet Synchronous Machine Parameters with Asymmetrical Power Voltage

Zhiyan Zhang[a, b], Hongzhong Ma[a], Jianbo Huang[c], Hongbo Qiu[b]

[a] College of Energy and Electrical Engineering, Hohai University, Fucheng West Road No. 8 Nanjing City Jiangsu Province, 210098, China,
[b] College of Electrical Information Engineering, Zhengzhou University of Light Industry, Dongfeng Road No. 5 Zhengzhou City Henan Province, 450002, China,
[c] School of Electrical Information Engineering Jiangsu University, Xuefu Road No.301 Zhenjiang City Jiangsu Province, 212013, China.
541046459@qq.com

Three phase power asymmetry caused by various reasons results in permanent magnet synchronous motor (PMSM) asymmetry running. The simulation model is established based on finite element analysis (FEA) software in order to analyze PMSM's various operation performance parameters both normal condition and asymmetry condition caused by single-phase power voltage sag, and the experimental and simulation results show that the relationship between output torque and power voltage sag is linear, and the output torque fluctuation is raised with aggravation of power asymmetry level; it is take a long time to make the PMSM run in steady state; the current of fault phase is degraded, and the fluctuation is raised, and the third harmonic of the fault phase is raised so significant compared with normal condition that it can be as a feature for fault diagnosis; the flux linkage of three phases is no remarkable change and the flux linkage of the fault phase has a little more obvious change than the other two phase; the PMSM output torque contains harmonic components caused by negative sequence component, and these results of the paper can provide the basis for catching fault character and regaining healthy operation as fast as possible.

1. Introduction

Compared with other motors, PMSM with no armature and slip ring has the advantages of simple structure and high reliability, and it with no current excitation and excitation loss has high efficiency, and it with no rotor fundamental iron loss and copper loss has high power factor which was confirmed (ZHANG Zhi-yan et al. (2015)), all which has been widely used in aviation, new energy vehicle, industrial production and so on. On the one hand, the running environment of PMSM is becoming more and more complex so that PMSM is affected by compound action of the electricity, heat and force. On the other hand, motor supply power is changed with the fluctuation of the power system load. These above factors are likely to make the PMSM parameters minor change in long-running so that operation parameters will be further worse if the operating environment has not been improved in time, which leads to the PMSM fault at last. Therefore, study of the change rules of the PMSM parameters in faulty state is important to early eliminate potential safety problems, particularly resume normal operation of the motor. The PMSM common faults include stator winding fault which was confirmed (J. Rosero et al. (2009)), permanent magnet demagnetization fault which was confirmed (J. Rosero et al. (2008) and Jordi-Roger Riba Rui et al. (2009)), bearing damage fault which was confirmed (J. Rosero et al. (2007 and 2008)) and the rotor eccentricity fault which was confirmed (Bashir Mahdi Ebrahimi et al. (2014)). Many scholars pay more attention to the performance change and fault diagnosis method of PMSM. PMSM internal faults, external faults and itself three-phase asymmetric parameters are likely to cause stator asymmetric operation, so that the stator asymmetric operation accounts for a larger proportion in PMSM fault running state.

PMSM internal electromagnetic parameters represent PMSM work characteristics, and the common three electromagnetic calculation models are respectively mathematical model, finite element analysis model and

Please cite this article as: Zhang Z.Y., Ma H.Z., Huang J.B., Qiu H.B., 2015, Affect on permanent magnet synchronous machine parameters with asymmetrical power voltage, Chemical Engineering Transactions, 46, 1033-1038 DOI:10.3303/CET1546173

equivalent magnetic circuit model. Construction of the equivalent circuit model or mathematical model is complicated because of PMSM’s nonlinear parameters, on the contrary the finite element simulation model is simple and various factors influence of the motor interior are considered, and the motor parameters consistent with the actual operation at higher degree from related literature, which provides support for PMSM fault diagnosis. Thus, the simulation model of PMSM is built using Ansoft platform in the paper, the change rules about output torque, three-phase current, three-phase flux and other parameters are gained by comparing normal condition with fault condition at different degree of unbalanced power single-phase voltage sag, and negative sequence voltage influence on PMSM performance is analyzed, at last the experimental platform is set up to verify the current parameters analysis results.

2. Simulation model establishment

The simulation motor is a PMSM used in pure electric vehicle by SAIC Motor which is a typical short winding structure that the pitch is 5 and the pole distance is 6 in order to minimize 5th and 7th harmonic, improve EMF waveform, and at the same time shorten the end connection line. The PMSM main structure parameters are that the type of PMSM is 270ZWS002, the number of poles is 8, the distribution of magnets is built-in V-shaped, the stator structure is double-layer with 48 slots, all which makes the winding electromotive force closer to sine wave; its main performance parameters are that the rated power is 42kW, the rated speed of 3000rmp, the rated input voltage 375V provided by the inverter, direct torque control, Y type non neutral winding connection type. The complete finite element analysis model using Ansoft/Maxwell software is established as is shown in Fig. 1(a). According to the motor symmetrical structure and the model simplification principle of FEM analysis method, two magnets of a pole are analyzed and modeled as is shown in Fig. 1(b), which can not only reduce the burden of computer operation, greatly accelerate finite element analysis speed and shorten analysis time, but also not affect on correctness and accuracy of the results.

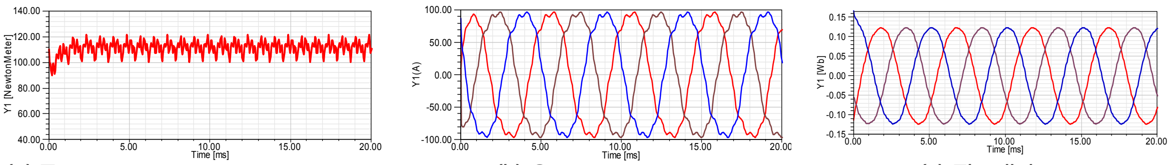
(a) The complete model *(b) The 1/8 model*

Figure 1: PMSM simulation model

3. PMSM parameters analysis under normal condition

Steady operation parameters determine the motor quality, which is an important reflection of the motor performance. Under normal condition, the output torque and the speed of PMSM are a constant or a very small fluctuation in the steady to meet the needs of various production conditions.

The model in Fig 1(b) is imposed on boundary condition and voltage source excitation condition which is three-phase symmetry 375V rated voltage, 200Hz rated frequency. In order to prevent current surge effect on the accuracy of simulation results and enable the simulation model to fast come into the stable state, the initial current values are respectively set to 0 (A), -87 (A) and 87 (A) after repeated calculation and debugging, and the simulation results are shown in Fig. 2.



(a) Torque *(b) Current* *(c) Flux linkage*

Figure 2: PMSM normal state waveform graph

4. PMSM parameters analysis under power voltage asymmetrical fault condition

The power voltage is symmetrical normally under normal condition, but when the power grid loads fluctuation or loads asymmetry, inverter power supply system fault or PMSM drive system fault the three-phase power voltage of the PMSM is no longer symmetry. In a certain range, the influence of the power voltage asymmetry is very small to the operation parameters of the PMSM, but when the power voltage asymmetry develops to a certain extent, the operation parameters such as torque, electromotive force, flux linkage and current, will have great change affecting on the operation performance of the motor.

A. Torque Analysis

The model in Fig. 1(b) is applied three-phase unbalanced power voltage which A phase voltage amplitude sags 75 (V) (20%) comparing with the normal power voltage, but B and C phase voltage amplitude are same as the normal operation, and the output torque under the fault condition is shown in Fig. 3.

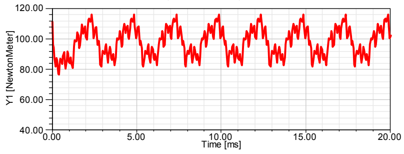


Figure 3: The output torque waveform graph under single-phase voltage 20% sag condition

Comparing Fig. 3 with Fig. 2(a), it can be seen clearly that the output torque has a larger fluctuation when the A phase voltage sags 20%, which is basically more 2 times than the normal operation state. The output torque amplitude decreased 10% more than the normal condition. It is take PMSM a long time to come into steady operation. To study the relationship between the voltage sags and the output torque, the PMSM are imposed different level asymmetrical three-phase voltage on the simulation model which A phase is respectively occurred in 5%, 10%, 15% and 20% sag, and the relationship between the sag of power voltage and the output torque of the PMSM is shown in Fig. 4.

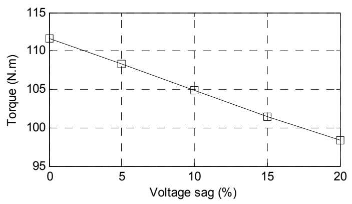


Figure 4: The relationship between voltage sags and output torques

As is shown in Fig. 4, the output torque decreases with the voltage sags increasing, and the relationship between them is roughly linear, because the positive sequence component of the three-phase current decreases and the negative sequence component increases when the single-phase voltage sags, all which leads to the PMSM air gap magnetic field reduce making the output torque have obvious decrease as the voltage sags increase.

B. Current Analysis

In control system, the PMSM electromagnetic torque is proportionate to the flux generated by the permanent magnet and stator current, therefore flux and current is important parameters of PMSM torque control system. The torque control of PMSM is actually a parameter analysis and adjustment of the observed flux or current, which directly affect on the control performance of the motor. Analysis the change rule of the flux and current parameters of PMSM under normal and fault state is a prerequisite for the motor torque accurate control. The current when A phase input voltage sags by 75 (V) (20%) in the simulation model is shown in Fig. 5.

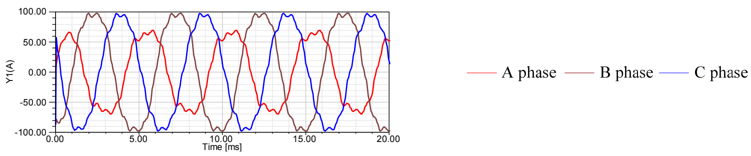


Figure 5: The current waveform graph under single-phase voltage 20% sag fault condition

Fig. 5 shows that under the fault condition A phase current of the stator has significantly decreased and three-phase current is serious asymmetry. Compared with Fig. 2(b), the PMSM current under the normal operation state, fault phase stator current distortion is intensified. In view of the three-phase current under normal condition is symmetrical, so harmonic analysis is done only for A phase. A phase current FFT analysis under the normal in Fig. 2 (b) and the three-phase current FFT under the fault condition is shown in Fig. 6.

(a) A phase current waveform under normal and fault condition *(b) Three-phase current comparison under fault condition*

Figure 6: Current harmonic comparison

Fig. 6 shows that the current waveform is close to sine wave, its fundamental content reach 99.6%, and the harmonic content is small under the normal condition. Hence the simulation model is correct. As is shown in Fig. 6(a), A phase current fundamental wave amplitude declines by about 28% because A phase voltage sags, and the total harmonic content increased from 26% to 37% which was mainly due to the 3 harmonic content increased by 4.65%, obviously A phase current amplitude decline is more than A phase voltage amplitude decline. From Fig. 6(b) it can be seen that B phase and C phase current harmonic component have variety, but less than A phase current harmonic component.

C. Flux Linkage Analysis

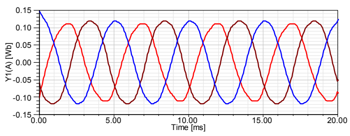


Figure 7: The flux linkage waveform graph under single-phase voltage 20% sag fault condition

The flux linkage is shown in Fig7 under the fault condition. From Fig. 2(c) and Fig.7 flux waveform diagram, it can be seen that the air gap flux linkage under the fault condition has small change in contrast with the normal condition and they are all sine waves basically. But the three-phase flux is no longer symmetric under the fault condition, the three-phase flux amplitudes has a different degree of reduction which is not proportional to the voltage sag, and the variety of heath phases stator winding flux linkage is relatively smaller than the fault phase flux variation.

PMSM flux linkage equation can be expressed as (1).

$$\begin{bmatrix}\Psi_A\\ \Psi_B\\ \Psi_C\end{bmatrix}=\begin{bmatrix}L_{AA} & M_{AB} & M_{AC}\\ M_{BA} & L_{BB} & M_{BC}\\ M_{CA} & M_{CB} & L_{CC}\end{bmatrix}\begin{bmatrix}i_A\\ i_B\\ i_C\end{bmatrix}+\begin{bmatrix}\Psi_{fA}\\ \Psi_{fB}\\ \Psi_{fC}\end{bmatrix} \tag{1}$$

In the formula(1), M_{AB}, M_{BC} and M_{AC} respectively represent the mutual inductance between three-phase windings; L_{AA}, L_{BB} and L_{CC} respectively represent three-phase winding inductance; Ψ_{fA}、 Ψ_{fB} and Ψ_{fC} respectively represent three-phase winding flux linkage produced by permanent magnet which associates only with permanent magnet condition and occupy a bigger proportion in flux linkage. Both in normal and fault states flux linkages are equal. The first term of PMSM flux linkage equation associates with the stator current, so flux linkages produced by three-phase current is no longer symmetric and they all have different level decline under the fault condition, which depends on the amplitude of fault phase current. The parameters in Fig. 7 and Fig. 2(b) are analyzed by FFT are shown in Tab. 1.

Table 1: The main harmonic distribution *of the flux linkage* (*unit:* $\times 10^{-4}$*Wb*)

Harmonic times		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Normal condition		843.04	2.19	17.07	1.49	2.26	0.94	0.80	0.21	7.41	0.57
Fault condition	A	785.75	3.37	35.69	1.85	4.91	1.01	1.18	0.65	6.75	0.86
	B	844.07	3.19	20.17	1.71	2.83	0.86	1.17	0.45	6.57	0.70
	C	842.28	3.03	19.55	1.69	3.12	0.99	0.65	0.64	7.22	0.83

As is shown in Tab. 1, A-phase flux linkage fundamental component is decreased by about 8% which is less than A phase voltage and current sag degree; B phase and C phase harmonic component is almost the same variety, all which is less than the harmonic component basically consisting with theoretical analysis.

D. Negative Sequence Component Analysis

In order to separately analyze the influence of various phase sequence on the PMSM performance, the voltage source excitation applied to the simulation model under fault condition is analyzed by the method of symmetrical components, and the principle can be expressed as (2).

$$\begin{bmatrix} \dot{V}_{a(+)} \\ \dot{V}_{a(-)} \\ \dot{V}_{a(0)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \dot{V}_A \\ \dot{V}_B \\ \dot{V}_C \end{bmatrix} \tag{2}$$

Where a equals to $e^{j120°}$, subscripts +, －,0 represent positive sequence, negative sequence and zero sequence respectively. Subscripts A, B and C represent corresponding A, B and C phase. When A phase voltage is sagged by 20%, $\dot{U}_A^+ = 350\angle 0°(V)$, $\dot{U}_A^- = 25\angle 180$ and $\dot{U}_A^0 = 25\angle 180°(V)$ according to formula (2). As can be seen from the analysis results, A phase voltage sag will not only reduce positive sequence voltage amplitude, but also will generate negative and zero sequence voltage components. Negative sequence voltage component will produce a reverse torque whose frequency is equal to the positive one, which makes the output torque generate a larger fluctuation. The rotation direction of negative sequence magnetic field is contrary to the rotor rotation direction and its magnetic torque is a braking torque, which increases the additional losses of rotor resulting in output electromagnetic torque decline, efficiency decrease, and heat augment. At the same time, the existence of negative sequence component aggravates the PMSM output torque fluctuation, which causes the PMSM bearing and core bear great uneven stress, so that the winding appears asymmetry current which contains a lot of harmonic resulting in winding heat aggravated and PMSM service life shorten.

5. Experiment verification

The test motor is PMSM which is consistent with the simulation motor, and experimental platform is shown in Fig. 8. The three-phase power wires are fitted with three Holzer current sensors CS050EK1 and Holzer voltage sensors VSM400DP, the data acquisition instrument outputs voltage signal, and the sampling frequency is 10kHz which can meet fault analysis and accuracy requirements. In Fig.8, the computer has two functions, receiving the current signal captured from the data acquisition instrument and controlling the PMSM operation station by given torque through the CAN bus.

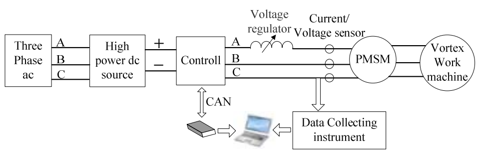


Figure 8: PMSM asymmetry fault experimental block diagram

The PMSM power voltage is changed by adjusting the voltage regulator on the experiment setup and A phase voltage sag of 75V (20%) is used to simulate the fault condition. The three-phase stator currents are collected under normal and fault conditions by the current sensors. The three-phase of simulation current waveforms and experimental measured current waveform under the fault condition is shown in Fig. 9. It can be seen from Fig. 9 that the experiment current data fit perfectly the simulation data. The local amplification waveform indicates that the experimental wave peak is smoother than the simulation wave, and the reason may be that the simulation model is established on some assumptions such as neglect of PMSM end effect and magnetic field along the axial uniform distribution, and actual model has done some approximate treatment. Non fault phases measured waveform is not the standard sine wave, which may influenced by the experiment environment and experiment equipment. When A phase voltage sags by 20%, A phase current is reduced by nearly 30% compared with the normal current, and it consistent with the simulation results.

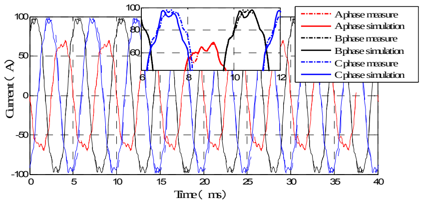


Figure 9: Experimental and simulation current waveform comparison

6. Conclusions

PMSM asymmetric operation has many reasons, in which three-phase power voltage asymmetry is mainly reason, so the paper studied this problem. The simulation model of the PMSM is established, and asymmetric fault state operating parameters of the PMSM caused by single-phase voltage sag are analyzed, compared with the normal operating parameters, and obtained the following conclusions:
(1) The relationship between the PMSM output torque and power voltage sag under the fault state is approximately inversely proportion; the output torque fluctuation is obviously increased along with the fault severity degree; the output torque contains frequency harmonics because of the negative sequence component existed in power voltage, which affects the operation performance of the PMSM.
(2) The results of simulation and experiment show that the three-phase current is no longer symmetric under the fault state, and the waveform basically retains its shape of sine; fault phase current fundamental wave amplitude decline scale is more than fault phase voltage sag scale, and the current wave has been apparently distorted, in which the 3rd harmonic component is increased obviously.
(3) The three-phase flux linkage fundamental has a certain degree variety under the fault condition, but far less than the voltage and the current sag extent, and non fault phase flux linkage amplitude change is more smaller, the harmonic content of the non fault phase flux linkage also changes, in addition, the flux linkage parameters could not be monitor, so it can not be a character in voltage sag fault diagnosis, but it is worth noting that it will be reflected in motor control system.
(4) The three-phase power voltage asymmetry fault will result in the negative sequence component of the PMSM operation parameters. Both negative sequence component increase and positive sequence component decrease will enable the PMSM air gap flux of fault phase reduce, lead to the PMSM performance deterioration. But the existence of negative sequence component provides a diagnosis method for the motor asymmetry fault.

References

Ebrahimi B.M., Roshtkhari M.J., Faiz J., et al, 2014, Advanced Eccentricity Fault Recognition in Permanent Magnet Synchronous Motors Using Stator Current Signature Analysis, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, 61(4), 2041-2051, 10.1109/TIE.2013.2263777.

Ruiz J.R.R., Rosero J.A., Espinosa A.G., et al, 2009, Detection of Demagnetization Faults in Permanent-Magnet Synchronous Motors Under Nonstationary Conditions, IEEE TRANSACTIONS ON MAGNETICS, 45(7), 2961-2969, 10.1109/TMAG.2009.2015942.

Rosero J., Cusido J., Ortega J. A., et al, 2007, PMSM Bearing Fault Detection by means of Fourier and Wavelet transform, The 33rd Annual Conference of the IEEE Industrial Electronics Society, Taipei, Taiwan. 1163-1168, 10.1109/IECON.2007.4460324.

Rosero J., Romeral L., Ortega J. A., et al, 2008, Demagnetization Fault Detection by means of Hilbert Huang Transform of the stator current Decomposition in PMSM, 2008 IEEE International Symposium on Industrial Electronics, Cambridge, United kingdom, 172-177, 10.1109/ISIE.2008.4677217.

Rosero J., Romeral L., Ortega J. A., et al, 2009, Short Circuit Detection by means of Empirical Mode Decomposition and Wigner Ville Distribution for PMSM running under dynamic condition, IEEE Transactions on Industrial Electronics, 56(11), 4534-4547, 10.1109/TIE.2008.2011580.

Rosero J., Romeral L., Cusido J., et al, 2008, Fault Detection of Eccentricity and Bearing Damage in a PMSM by means of Wavelet Transforms Decomposition of the Stator Current, 23rd Annual IEEE Applied Power Electronics Conference and Exposition, Austin, TX, 111-116, 10.1109/APEC.2008.4522708

Zhang Z.Y., Ma H.Z., Yang C.X., et al, 2015, Demagnetization fault diagnosis in permanent magnet synchronous motor combination wavelet packet with sample entropy, 19(2), 26-32, 10.15938/j.emc.2015.02.005