Development of A Super High-Speed Permanent Magnet Synchronous Motor (PMSM) Controller and Analysis of The Experimental Results

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ABSTRACT

This paper presents the design and implementation of a DSP-based controller for a super high-speed (>80,000 rpm) permanent magnet synchronous motor (PMSM). The PMSM is a key component of the centrifugal compressor drive of a reverse Brayton cryocooler that is currently under development for NASA and Florida Solar Energy Center. The design of the PMSM open-loop control is presented. Experimental results with open-loop control schemes are presented. System optimization and analysis are also illustrated. They verify the effectiveness of the controller design and the optimization scheme.

Keywords: super high-speed, permanent magnet synchronous motor, high efficiency, optimization, open-loop control.

1. IMPORTANT INFORMATION

Super high speed motors are becoming more and more attractive in many applications such as centrifugal compressors and spacecraft in recent years. Many kinds of motors can be considered for such applications. Induction motor (IM) is a low cost and easy option but with relatively low efficiency at high speed due to the higher iron loss in the rotor [1]. Switched reluctance motor has high reliability with simple and robust rotor structure [1], however, the iron loss is very critical at high speed. Although several compact blushless direct current (BLDC) motors are used in such cases because of easy control and high power density, the requirement of high efficiency (to achieve about 95% efficiency of the control electronics) makes it impossible for many industrial applications such as cryogenic coolers. However, Permanent Magnet Synchronous Motor (PMSM) is different. Due to low harmonics of the induced electromagnetic force (back EMF), no excitation power loss in the rotor and only low eddy current loss in the stator and rotor exist. Using slotless stator structure also eliminates the cogging torque. High efficiency PMSM for super high speed is possible.

Thanks to rapid progress in power and microelectronics and advanced motor design methods, high efficient super high-speed PMSM controllers are possible. However, many challenges are still posed for such super high-speed PMSM controller design because of its super high-speed, variable speed operation, and requirement of stable control over a wide speed range. Currently, limited research is available concerning high speed PMSM and its control system design. No experimental results and analysis is available.

Experimental experience gained from a DSP-based digital controller for a PMSM motor (up to 80K RPM) is introduced in this paper. A testing system for the super-high speed PMSM has been built and feasibility of open-loop control modes has been examined. The optimization of software implementation is also covered.

The permanent magnet synchronous motor specification will be present at first in this paper. Method and design of the open loop control system follows. Then, experimental results and analysis are presented to confirm the theoretical developments and demonstrate the feasibility of the practical implementation. Finally, conclusions are given.

2. PMSM

In Permanent Magnet Synchronous Machine, the field of winding of the synchronous machine is replaced by permanent magnets. This approach increases the efficiency of the machine and reliability due to the elimination of rotor winding maintenance. It also results in smaller size, less weight and higher torque to size ratio.

For PMSM motors, the number of poles is an important specification. It has a directly reverse relationship with motor highest speed. The relationship of motor speed and the number of poles is:

$$V = 120 * f/p \qquad (1)$$

V is motor speed, which is in RPM
f is motor input frequency
p is the number of poles

With fewer poles, motors can be driven to higher speed in same condition. However, if the number of poles decreases, the size of the motor will increase. To balance the requirement of super high speed and extra small size in this project, a 4-pole PMSM motor design is selected. The target speed of the 100W PMSM motor is 100,000 RPM with a bus voltage of 28V. Efficiency of the PMSM motor and controller system needs to go above 90%. The PMSM system is a key component of the reverse Brayton cryocooler that is currently under development at the University of Central Florida, which is supported by NASA Kennedy Space Center and Florida Solar Energy Center.

3. CONTROLLER DESIGN

The proposed open loop control system is shown in Fig.1. In this development, TI TMS320LF2407A digital signal processor is employed to produce Space Vector Pulse Width Modified (SVPWM) control signal. SVPWM method is chosen because of its high efficiency and low harmonic properties. A constant volt per hertz (*V/f*) control scheme is implemented to control motor speed.

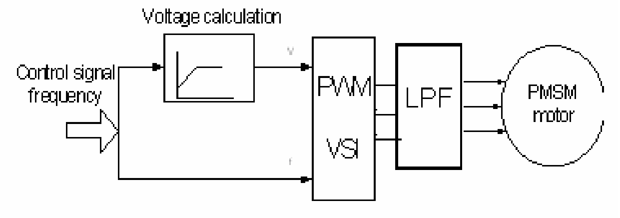

Fig.1 Proposed open loop *v/f* control approach

V/f Control

V/f control approach is employed due to low cost and simple design, which is advantageous in the middle to high speed range [2].

In the *V/f* control method, motor speed is controlled by both the magnitude and frequency of stator voltages, which always maintain the air gap flux at the desired steady-state level. The magnetizing current, denoted as I_m, that generates the air gap flux Λ_m, can be approximately presented by the ratio of stator voltage to frequency. At steady state status, its phasor equation can be written as:

$$I_m \cong \frac{V}{\omega L_m} = \frac{V}{2\pi f L_m} \qquad (2)$$

$$I_m = \frac{\Lambda_m}{L_m}$$

L_m is a constant because motor is assumed to be operating in linear magnetic region. So, we can get

$$\Lambda_m \propto \frac{V}{f} \qquad (3)$$

To keep the air gap flux Λ_m a constant, that is to keep the magnetizing current I_m as a constant, the ratio of stator voltage over the corresponding frequency must be a constant at different speeds. This approach is also called constant volts per hertz control. As the motor speed increases, the stator voltage need be proportionally increased in order to keep the ratio *V/f* constant. If motor speed is higher than the motor rated frequency, f_{rated}, the *V/f* ratio cannot be kept at a constant value because of the limit of the stator voltage. Therefore, the air gap flux is reduced consequently. This reduces the output torque further. This region is usually called the field-weakening region. A typical *V/f* profile is shown in Fig.2.

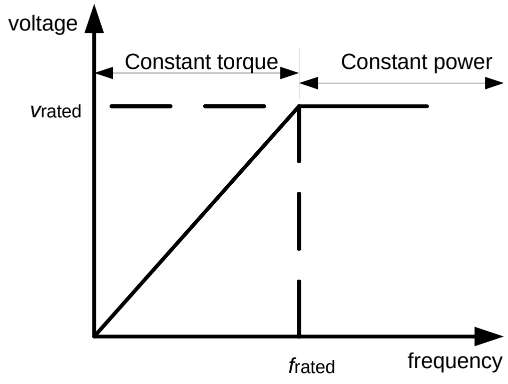

Fig.2 A typical *V/f* profile

In practice, at low frequency and voltage, voltage drop across the stator resistance cannot be neglected and it must be compensated. So, it is important to have a suitable starting voltage. Correspondingly, the *V/f* profile is modified as Fig.3.

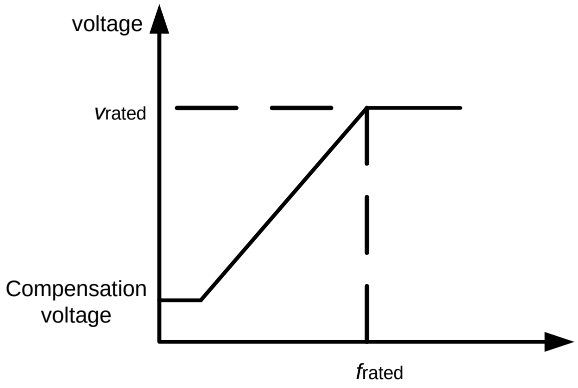

Fig.3 A modified *V/f* profile

SVPWM

Because of the PWM inverter, it is possible to modulate both signal frequency and voltage magnitude in high switching frequency due to advances in microprocessor and semiconductor. The PWM inverter provides higher efficiency and better performance compared to fixed frequency controller [3], [4]. Several PWM techniques are most commonly used: sinusoidal PWM, hysteric PWM and Space vector PWM.

The Space Vector Pulse Width Modulation (SVPWM) technique, which was proposed in recent years, refers to a special way to determine switching sequence of the three-phase voltage source inverters. It uses basic space vectors to generate the output voltages to the motor. The space vector PWM technique has been shown to generate less harmonic distortion in output voltages and currents. In addition, it provides a more efficient use of the supply voltage compared to sinusoidal PWM technique.

For a three-phase voltage source inverter (VSI), shown in Fig.4, V_a, V_b and V_c are the output voltage, which will modulate PMSM motor speed. M_1, M_2,… through M_6 are power transistors which are controlled by gate signal and decide the output. When the upper transistor is turned on, i.e. *a*, *b* or *c* is 1, the lower side is turned off, i.e. *a'*, *b'* or *c'* is 0. SVPWM is to determine the switching sequence of upper sides. The on and off status of the three upper transistor compose eight possible vectors. The eight vectors are called the Basic Space Vectors. They are denoted by U_0, U_{60}, U_{120}, U_{180}, U_{240}, U_{300}, O_{000} and O_{111}, as shown in Fig.5. There are six non-zero vectors and two zero vectors. The six nonzero vectors form a hexagon. The angle between any two adjacent non-zero vectors is 60 degrees. The two zero vectors are at the original point.

In the basic space vectors diagram, the rotating reference VSI output voltage, denoted U_{out}, can be shown on a stationary locus between two adjacent space vectors for any short amount of time. The combination of two switching states can be used to instantaneously represent the reference voltage as long as this period of time is much smaller than the reference voltage rotating speed.

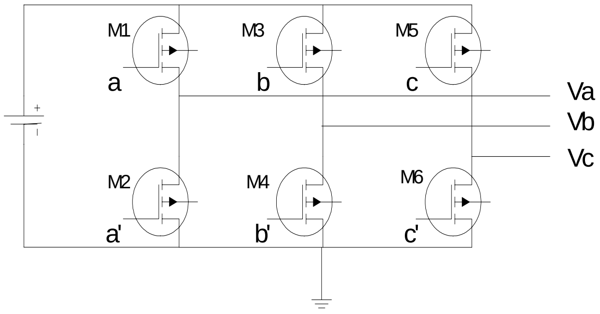

Fig.4 A three phase voltage source inverter

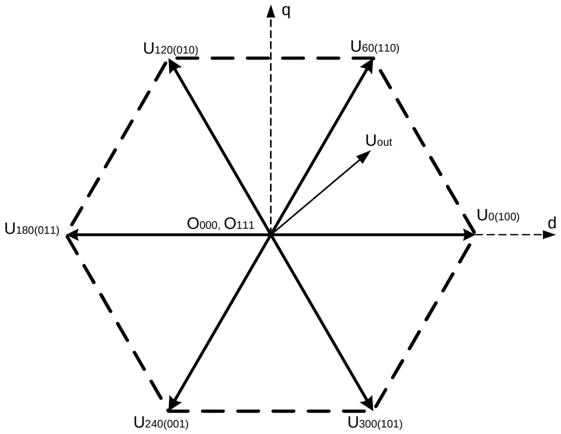

Fig.5 Basic Space Vectors

Due to the low phase inductance of the slotless structure and inductance load requirement of PWM inverter, a L low pass filter is used in the control circuit board.

4. EXPERIMENT AND ANALYSIS

Experiments up to 80,000 RPM using the proposed PMSM motor controller test system were done. Effort and optimization were given to increase the speed of the motor. A low cost DSP chip, TI TMS320LF2407A that runs at 40M HZ clock, was employed. Fig. 6 provides the motor phase current waveform at 50,000 RPM. The analysis of the phase current I_c harmonics is given in Fig. 7. In this figure, the most prominent harmonic, 5^{th}, RMS value is only 5.88% after normalized, which is ignorable. It shows the effectiveness of the proposed scheme.

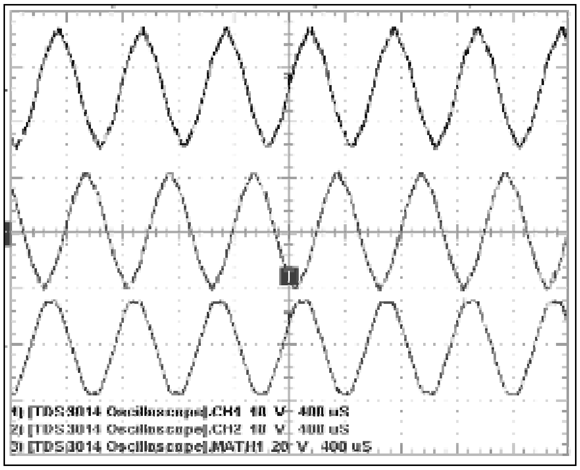

Fig. 6 Motor phase voltage V_a, V_b and phase current I_c waveforms at 50,000 RPM

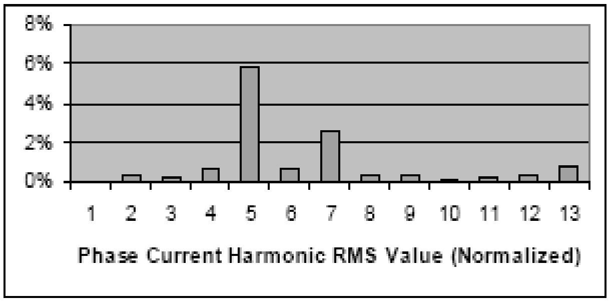

Fig7. Phase current I_c harmonic analysis

When the motor speed increases beyond 60,000 RPM, more input power has to be provided to the motor to make it run smoothly and approach higher speeds.

Several system optimizations have been tested and employed. As we known, high switching frequency always means good result in theory. However, more switching loss will dissipate in inverter with increasing switching frequency. More *dv/dt* noise happens also occurs. And it also requires that every component in the whole system have excellent dynamic characteristics. But motor efficiency will increase due to lower core loss[5], [6], [7]. Simulation and test and are done to make the balance. The result shows that the system performances are almost the same when switching frequency is within some range. Detailed analysis of the switching frequency effect for whole system exceeds the coverage of this paper.

Programmable dead time is added to avoid short circuit. This occurs in the voltage source inverter due to charging and discharging MOSFET capacitors. Simulation shows that dead time affects performance to some extent after exceeding some value. Dead time also makes inversion nonlinear. Some methods can be implemented to compensate such effects [8], [9].

An extra low pass filter is needed to eliminate harmonics and also compensate low motor phase inductance. A simple, reliable L design is used. In industry, it is all a rule of thumb – the harmonic is not harmful once it falls under 5%. Simulation is used to find the inductance. Test results further prove it. The phase current FFT waveform is shown next. The harmonic is ignorable.

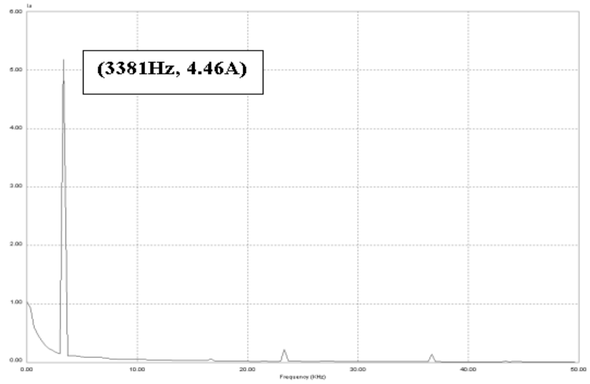

Fig8. Phase current FFT waveform with L=50uH

5. CONCLUSIONS

This paper has presented the development of a super high-speed permanent magnet synchronous motor controller. The PWM control system design and approach were elaborated. Experimental results up to 80,000 RPM were followed. The practical implementation confirmed the feasibility of theoretical developments and demonstrates the approach correct. At last, system optimization and analysis were presented.

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