Analysis of Three Synchronous Drive Modes for the Starting Performance of Spindle Motors

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In sensorless operation of spindle motors in hard disk drives (HDD), open-looped starting is used to spin up the motor from standstill to a speed that is high enough to reliably detect back-electromotive force (back-EMF) generated in the armature windings. Then the back-EMF zero-crossing points (ZCP) will be used to detect speed and position for closed-looped control. This paper studies three open-looped starting modes for spindle motor. Six-step, which is currently used in HDD, twelve-step, and sine wave starting are illustrated and compared. The simulation results show that twelve-step and sine wave starting can obtain much better starting performance for spindle motors.

***Index Terms*—Open-looped starting, six-step starting, spindle motor, twelve-step starting.**

I. INTRODUCTION

THE spindle motor used in hard disk drives (HDDs) is a typical three-phase permanent magnet synchronous motor. One great concern in the HDD industry in using the spindle motor is its starting capability. The major reasons that make motor starting difficult in the modern HDD include:

1) Fluid dynamic bearing is used in the motor and this leads to the increased friction torque in motor starting.
2) Though the DC-link voltage of the drive is kept the same, the rated speed of the motor is becoming higher and higher. Therefore, its torque constant is becoming smaller and smaller. To produce enough starting torque, a high starting current should be used in motor starting, but it is limited by the power electronics devices used.
3) The HDDs used in mobile system are required to start operating at an even faster rate.

In HDD, the spindle motor is operated with sensorless drive method, which is based on detecting the motor back-EMF ZCP signals for estimating speed and position, and this method cannot work at zero speed. Therefore, an open-looped starting technique has to be used to first spin up the motor from standstill to a speed high enough so that the back-EMF can be reliably detectable, after which it can be switched to the closed-looped drive mode.

Starting methods presented in previous literature can be grouped as: 1) start-up methods using current injection [1]–[3]; 2) start-up methods using a known initial position [4], [5]; and 3) start-up methods using frequency- and/or voltage-skewed drive signal [6], [7]. The methods in [1] and [2] are similar. Some currents are injected and the current amplitudes are detected, which vary at different positions under different magnetic poles. Then the rotor position can be calculated. Since almost all the spindle motors nowadays use surface mounted permanent magnet, these methods may not be effective. Two types of pilot voltage patterns are used in [3] in order to detect the initial position, and current peak detection circuits are also needed. The resource limitation in HDD determines that this method is undesirable. The known initial position method either requires intensive calculation [4] or align rotor axis to some place with certain voltage pattern [5]. Since the calculation power in HDD is very limited and the torque constant is getting smaller as motor speed goes higher, these methods are no longer used in HDDs.

The skewed voltage method requires less calculation and is easy to implement, so it has been used in HDDs. So far, the widely adopted starting method in HDDs is called six-step open-looped starting with skew frequency, or SSS in short, i.e., the six-step switching frequency is gradually increased to force the rotor to follow. However, due to the smaller torque constant and the use of FDB whose friction torque is relatively large at low speed, the frequency has to be carefully skewed, with longer starting time to ensure successful starting. Improvement of the starting capability thus becomes more and more of concern in the HDD industry. In our experiments, it was discovered that increasing the stepping number in one EM cycle can conclusively improve the spindle motor starting performance. Therefore, different starting methods with different switching steps in one EM cycle should be studied.

In this paper, another two different open-looped starting methods, namely twelve-step starting (TSS) and sinusoidal wave starting (SWS), are studied and compared with the SSS.

II. THREE OPEN-LOOPED STARTING MODES

In the SSS, the inverter is switched every 60 degrees and there are 6 steps in one cycle. To make the explanation easier, a simple inverter circuit is depicted in Fig. 1. The sequence of gate open signal pairs is thus shown in Table I. In this mode, the phase voltages of the motor look like those in Fig. 2 with 120 degrees conducting. At low speed, the back-EMF is relatively small and the effect of inductance can be neglected. Therefore, the phase current will look similar to the voltage shape as shown in the experimental results in Fig. 3.

Just as its name implies, the TSS mode consists of a total of 12 steps in one cycle. An additional status with three phases conducting is inserted in between every two successive statuses in SSS so that the inverter is switched every 30 degrees. The switching sequence is also listed in Table I.

The phase voltage in TSS is now 150 degree conducting and it is illustrated in Fig. 4 and the experimental results are shown

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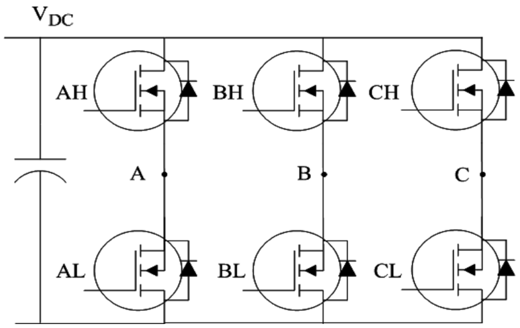

Fig. 1. Three-phase inverter circuit.

TABLE I
SWITCHING SEQUENCES IN SSS AND TSS

	Switching Sequence
SSS	(AH BL) (AH CL) (BH CL) (BH AL) (CH AL) (CH BL)
TSS	(AH BL) (AH BL CL) (AH CL) (AH BH CL) (BH CL) (BH CL AL) (BH AL) (BH CH AL) (CH AL) (CH AL BL) (CH BL) (AH CH BL)

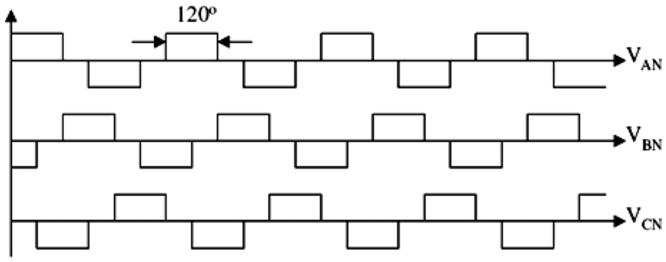

Fig. 2. Three-phase voltage in SSS.

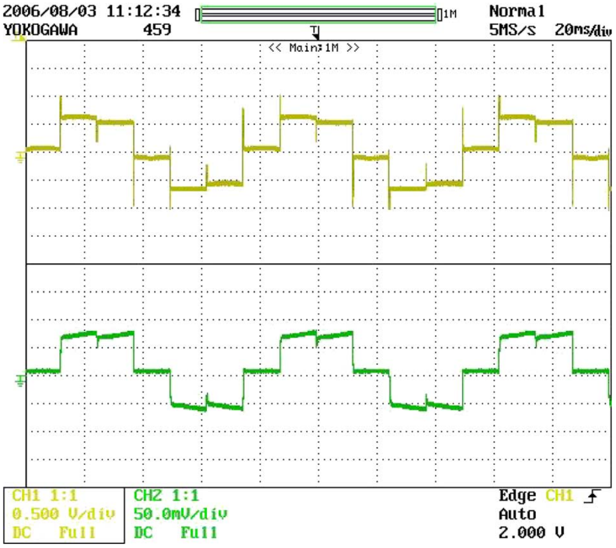

Fig. 3. Experimental result of one-phase voltage and current in SSS.

in Fig. 5, in which the current wave form is close to the shape of the voltage due to the small back-EMF and inductance.

The major difference between the SSS and TSS is the current change between two successive switching steps, which is illustrated in Fig. 6.

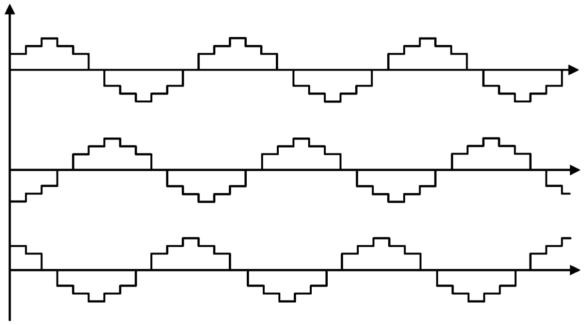

Fig. 4. Three-phase voltage in TSS.

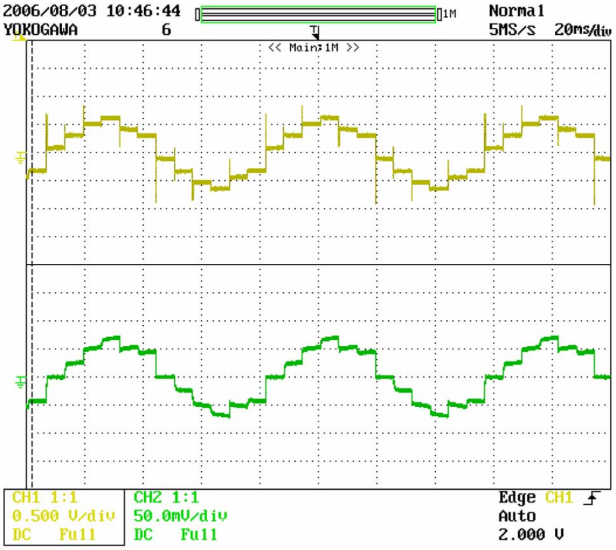

Fig. 5. Experimental result of one-phase voltage and current in TSS.

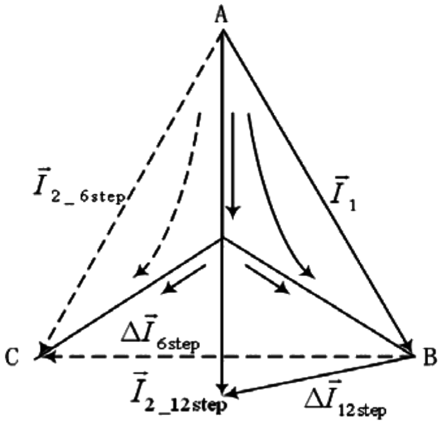

Fig. 6. Current vector in the SSS and TSS.

Suppose in the previous step, the current flows from A to B and the current vector is $\vec{I}_1$. In the next step of the SSS, the current flows from A to C and the corresponding current vector will be $\vec{I}_{2-6step}$. Therefore, the current variation vector in SSS is $\Delta\vec{I}_{6\mathrm{step}}$ as shown in dashed line. In contrast, the current flows from both A to C and A to B in the next step in TSS and it is illustrated as $\vec{I}_{2-12\mathrm{step}}$ and the current variation vector as $\Delta\vec{I}_{12\mathrm{step}}$. From the vector variations in both SSS and TSS, it is clear that the magnitude of the current vector variation is much smaller

TABLE II
MOTOR PARAMETERS USED IN SIMULATION

Pole pair	6
Rated speed (rpm)	5,400
Inertia (g.cm^2)	30
Torque constant (mNm/A)	8.0
Phase-to-phase resistance (Ω)	3.0
Phase-to-phase inductance (mH)	1.3

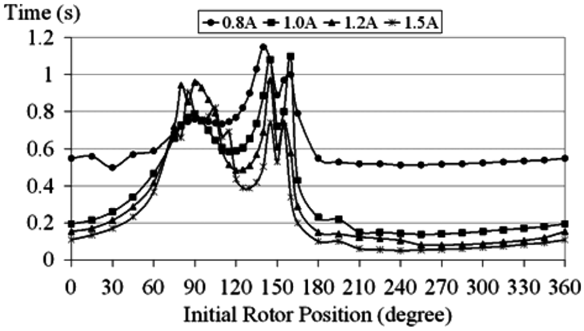

Fig. 7. Starting time of SSS against different initial rotor positions.

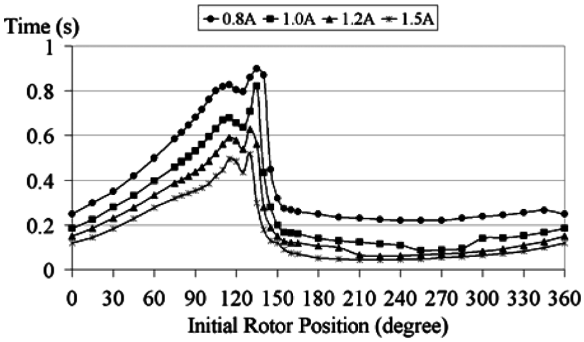

Fig. 8. Starting time of TSS against different initial rotor positions.

in TSS than in SSS, and the current change angle, 60 degrees in SSS and no greater than 30 degrees in TSS, is also greatly reduced, which means the magnetic torque produced could possibly vary more smoothly in TSS than in SSS. Consequently, in the TSS, it is less possible to excite resonance of the rotor during the open-looped starting process, which could make the starting easier and smoother.

It is herein logical to ask what if the switching steps are increased further. Could the starting performance be even better? To answer the question, another open-looped starting mode, SWS with pure sinusoidal drive voltage is also studied, which can be seen as infinite switching steps. In this mode, continuous sinusoidal current is injected into all three stator windings.

III. SIMULATION RESULTS

The motor starting capability of these three starting modes is simulated and compared at four different starting currents, 0.8 A, 1.0 A, 1.2 A, and 1.5 A, with different initial rotor electrical positions from zero to 360 degrees with 15 degree interval. The zero degree is chosen to be aligned with the phase A axis. The motor parameters used in the simulation are listed in Table II.

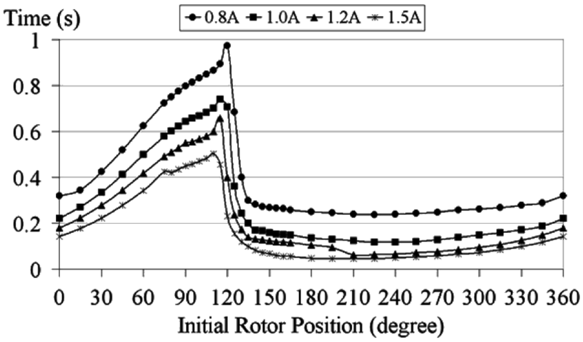

Fig. 9. Starting time of SWS against different initial rotor positions.

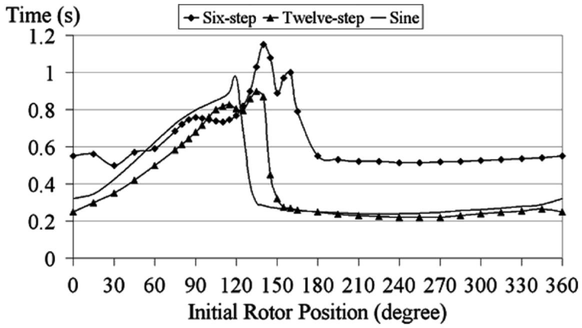

Fig. 10. Starting time of the three modes against different initial rotor positions at 0.8 A.

In the simulation, the target speed was set to be 800 rpm at which the motor back-EMF is considered to be reliably detected. The time needed for the motor to start from standstill to 800 rpm against different initial rotor positions at different starting currents in different starting modes are illustrated in Fig. 7–9. The simulation results show clearly that the spin-up time is usually reduced when the stating current is increased wherever the initial rotor position is, except that in SSS, higher starting current could cause longer starting time probably due to greater vibration effects in SSS.

To better compare the starting performance, the starting curves of the three modes are combined together at four different currents so that the starting time of these modes can be compared directly. Figs. 10–13 give the starting time of these three modes at four different starting currents against different initial rotor positions.

To compare the starting performance, three criteria were used:

- average starting time over 360 degrees;
- maximum starting time in 360 degrees;
- dangerous zone.

The phrase dangerous zone is used in HDD industry to define the initial rotor position range in which the spin-up time is longer than the expected. In the simulation, the expected time was set to be 0.4 s. The average starting time of the three modes over the 360-degree range is listed in Table III, maximum starting time in Table IV, and dangerous zone in Table V.

From the tables, it is clear that for the spindle motor with the parameters listed in Table II, the average starting time over the 360-degree range using TSS or SWS is much shorter than that of the SSS, achieving 30% to 50% reduction. The maximum starting time reduction using TSS or SWS is not as great

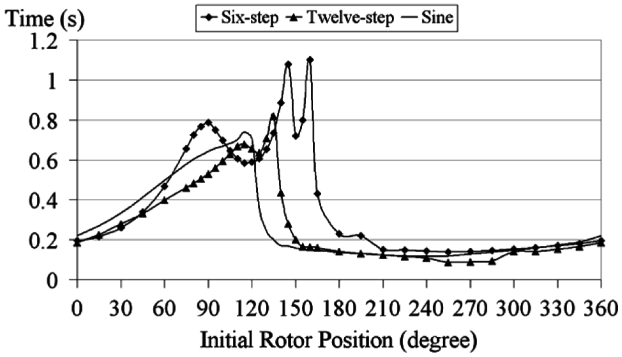

Fig. 11. Starting time of the three methods at the same starting current 1.0 A.

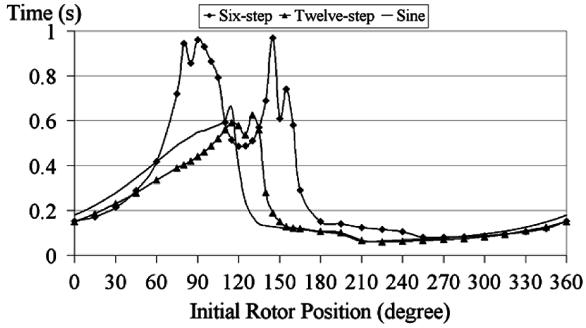

Fig. 12. Starting time of the three methods at the same starting current 1.2 A.

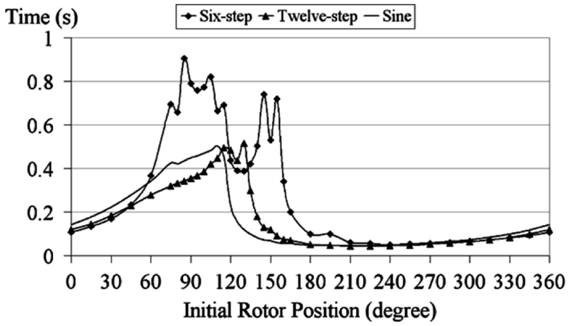

Fig. 13. Starting time of the three methods at the same starting current 1.5 A.

TABLE III
AVERAGE STARTING TIME (S) IN DIFFERENT STARTING MODES AT DIFFERENT STARTING CURRENTS

	0.8A	1.0A	1.2A	1.5A
SSS	0.69	0.47	0.43	0.36
TSS	0.46	0.34	0.27	0.21
SWS	0.46	0.32	0.26	0.19

TABLE IV
MAXIMUM STARTING TIME (S) IN DIFFERENT STARTING MODES AT DIFFERENT STARTING CURRENTS

	0.8A	1.0A	1.2A	1.5A
SSS	1.15	1.10	0.97	0.91
TSS	0.9	0.82	0.63	0.52
SWS	0.97	0.74	0.66	0.50

as average time reduction, which is about 20% less than SSS. The dangerous zones in SSS at any of the four starting currents are at least 50% wider than those in TSS and SWS. After increasing the starting current to 2.5 A in the simulation, the TSS can achieve zero degree dangerous zone performance. From the above figures and tables, it can also be seen that TSS and SWS gave fairly similar performance. It can thus be concluded that increasing switch steps further from twelve steps will not improve the spindle motor starting performance.

TABLE V
DANGEROUS ZONES IN DIFFERENT STARTING MODES AT DIFFERENT STARTING CURRENTS

	0.8A	1.0A	1.2A	1.5A
SSS	360°	120°	100°	90°
TSS	105°	80°	60°	40°
SWS	100°	80°	60°	50°

IV. CONCLUSION

The spindle motor starting performance is increasingly a matter of concern to the in HDD industry. Due to the sensorless operation and limited computational resource available in the HDD drive chips, open-looped starting is currently employed widely in HDDs to drive the spindle motor from standstill to a speed that is high enough to reliably detect its back-EMF. In this paper, three open-looped starting modes, SSS that is currently used in HDD, TWS and SWS are studied and compared. The criteria of average starting time, maximum starting time, and dangerous zone were used in the analysis to compare the starting performance of the different starting methods. The simulation results show that faster and smoother spin-up performance against different initial rotor positions can be achieved using TSS or SSS. The results also show that the starting performance of TSS and that of SWS are very close at different currents. Since TSS can be easily realized without any change to the SSS hardware configuration while realizing similar performance as the SWS does, the TSS could be a preferred choice for in the HDD drive system to improve the spin-up performance of spindle motors.

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