

Study of a Spindle Motor Starting Using Circuit-Field Direct Coupled System

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Abstract — This paper presents an analysis of the starting characteristics of the hard disk drive (HDD) spindle motor using circuit-field direct coupled system. In system level simulation, non-linear electromagnetic field equations, stator winding circuit equations, external control circuit and rotor kinetics are directly coupled and solved simultaneously. Hence, the solutions can take into account the complexity of the geometric model, non-linearity of the electromagnetic field, external control loop feature, eddy current effect, the material saturation and rotor rotation which are very difficult to consider all together in traditional analytical methods and magnetic circuit analysis. Proposed direct coupled model can be extended to use in investigating the transient performances of the electrical machine connected with external control circuits.

I. INTRODUCTION

The spindle motor is a key component of the HDD system and in many ways determines the drive capacity, reliability and performances [1]. HDD spindle motor generally requires high starting torque to overcome high friction and stiction forces caused by interaction between the magnetic heads and disks of HDD, and its bearing. This requirement becomes more strict for the spindle motors use fluid dynamic bearing (FDB), and form factor of HDD is small. However, to get the high starting torque, the starting current cannot be increased too much. It is severely limited by the computer power supply (modern PCs use very limited power packs) and other electronic limitations. In addition, starting time so called spin-up time (the amount of time that is required for the disk platters to get up the full rotational speed from a stationary start) is largely determined by the drive specifications and has to be very fast. Spin up time is directly related to PC boot speed and power management scheme. Hence, analysis of starting performances of the spindle motor is vital in the design and analysis of spindle system for HDDs.

Because of the high degree of complexity and the wide variety of domains involved in motor performance analysis, modeling and simulation is a preferred method. In both numerical and analytical aspects, finite element method (FEM) is by far the most efficient and popular technique and widely used in motor design and performance evaluation [2]-[5]. Accurate modeling of electrical machines requires simultaneous solution of the FEM equations and circuit equations of the windings. If electrical machines are connected to external circuits, additional circuit equations related with power electronics are also needed to couple into the machine

analysis model. In addition, when motor transients are considered, rotor mechanical effect should certainly be included in the analysis model, and all of the system equations are required to formulate and solve in time domain [6].

An attempt is made in this work to analyze the starting performances of the spindle motor by using circuit-field direct coupled system. In system level simulation, the non-linear electromagnetic (EM) field equations are directly coupled with the stator circuit equations, external circuit equations and the rotor motion equations then solved simultaneously in time domain. Cascaded speed and current loop controller is used in control loop simulation.

II. MODELING TECHNIQUES

HDD spindle motors are outer rotor type permanent magnet brushless DC motor and normally driven by the voltage source inverter as shown in Fig. 1.

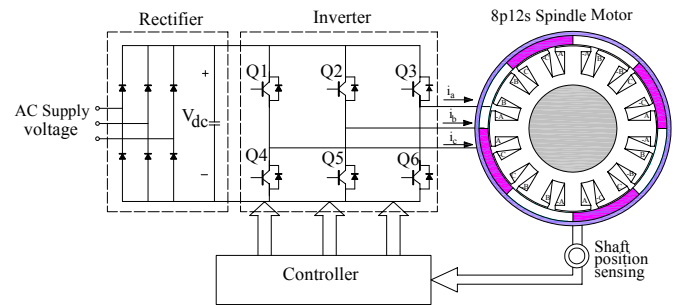


Fig. 1 Spindle motor configuration and drive system

Two phases windings out of three are energized at every commutation period and they are switched in a logical sequence by electronic controller. The impressed voltages comprised of a series of pulses of varying widths and the stator phase currents are non-sinusoidal. Hence, accurate modeling of the motor-controller system requires direct coupling and simultaneous solutions of the time varying EM field, stator winding circuit, the characteristic of the inverter circuit, control loop feature and rotor rotational effect in time domain.

Numerical modeling of the system level simulation can be divided into four main parts as follows.

- (1) Modeling of nonlinear EM field in time domain
- (2) Modeling of the electric circuit equations that represent the electrical sources and circuit components

- (3) Modeling of the rotor motion that have interaction with the EM field and
- (4) Modeling of the control loop and interaction with system level field-circuit equations.

A. Modeling of Non-linear Electromagnetic Field

The time dependent nonlinear EM field in a spindle motor can be represented by applying the Maxwell's equation as:

$$\nabla \times (\nu \nabla \times A) = J_s - \sigma \frac{\partial A}{\partial t} + \nabla \times (\nu B_r). \quad (1)$$

The first term of the right side of (1) represents for EM field of the stator conductor region, second term represents for iron cores region where eddy current cannot be ignored and the last term represents for permanent magnet region. In (1), A is the magnetic vector potential, ν is the reluctivity of the material, J_s is the applied current source density in the field domain, σ is the conductivity of the material and B_r is the remenent flux density of permanent magnet. The solution of field equation (1) is obtained by minimizing the corresponding nonlinear energy functional. The minimization is performed by means of FEM using first order triangular elements. Non linear time domain finite element formulation is discussed in section III.

B. Modeling of Circuit Equations

1) Modeling of external circuit

In power application, most of the external circuits connected to electric machines consist of semiconductor components, resistors (R), inductors (L) and capacitors (C). If the semiconductor components are modeled as resistors, the external circuits can be simplified as R - L - C circuits. The external circuits can be represented by several branches of circuits made up by resistors, inductors or capacitors. In forming the circuits, all the branches are connected by joints in series or in parallel as shown in Fig. 2, and the governing equation for external circuits can be expressed as [7]

$$\left\{ [R_{sb}] + \frac{d}{dt} [L_{sb}] \right\} [i_{sb}] + [C_{sb}] \frac{d}{dt} [V_{sb}; V_t] = 0, \quad (2)$$

where i_{sb} is the current flowing in all branches of the external circuits, V_{sb} is the terminal voltages of all joints and V_t is the terminal voltages of the electric machine. Generally, the semiconductor components (transistors and diodes) can be simulated in the switching mode as they are operated in the power electronics controllers. If set the settling time of the semiconductor devices are shorter than the time step length of the FEM, the switching devices can be simply represented by the nonlinear resistances corresponding to the forward conduction resistance in the 'ON' state and a high resistance to simulate the 'OFF' state [8]. Apply this technique in modeling the inverter circuit in this work.

2) Equivalent circuit equation of the stator winding

The stator phase circuit equation can be expressed in general form as:

$$V_s = Ri_s + L_\sigma \frac{di_s}{dt} + e, \quad (3)$$

where V_s is the stator phase voltage, R total equivalent resistance of the winding, i_s is the stator phase current, L_σ is the inductance of the end winding and e is induced voltage (back-emf) and can be represented by magnetic vector potential as:

$$e = \frac{l}{S} \left(\iint_{\Omega^+} \frac{\partial A}{\partial t} d\Omega - \iint_{\Omega^-} \frac{\partial A}{\partial t} d\Omega \right) \quad (4)$$

where l is the axial length of the iron core, Ω^+ and Ω^- are total cross-sectional area of the 'in' and 'out' side of the winding.

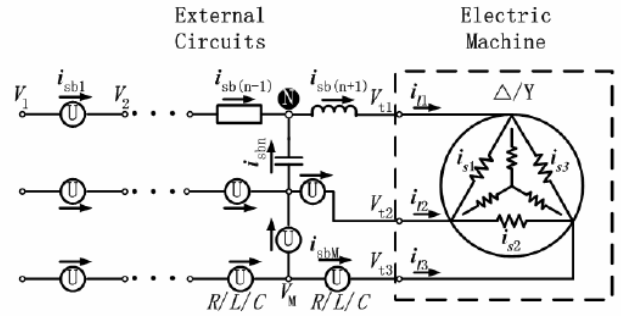


Fig. 2 Representation of external circuit connected with machine [7]

C. Modeling of Rotor Rotation

Rotor motion governed by the mechanical equation can be expressed as:

$$J \frac{d\omega}{dt} = T_e - T_L + d\omega, \quad (5)$$

and

$$\frac{d\theta}{dt} = \omega, \quad (6)$$

where J is the moment of inertia, ω is the rotor speed, T_e is the electromagnetic torque, d is the damping coefficient and T_L is the load torque.

III. FINITE ELEMENT FORMULATION IN TIME DOMAIN

Galerkin's method is used to derive the element matrix equations. According to the Galerkin's method, the magnetic vector potential, A for each element can be represented as,

$$A = \sum_{i=1}^m N_i A_i \quad (7)$$

where N_i is the element shape function, m are nodes in the element and A_i is the magnetic vector potential of the element.

Galerkin's form of the field equation (1) is

$$\iint \left[\frac{\partial N_i}{\partial x} \frac{\partial}{\partial x} \nu \sum_{j=1}^3 N_j A_j + \frac{\partial N_i}{\partial x} \frac{\partial}{\partial x} \nu \sum_{j=1}^3 N_j A_j \right] = N_i \left(\frac{i_s}{S} \right) - \iint \left[\sigma N_i \left(\frac{\partial A_i}{\partial t} \right) \right] dx dy + \iint \left[\nu \mu_0 \left(M_x \frac{\partial N_i}{\partial y} - M_y \frac{\partial N_i}{\partial x} \right) \right] dx dy \quad (8)$$

We can represent in matrix form as,

$$\nu [G] \{A\} = \{Q\} \frac{i_s}{S} - \sigma [T] \left\{ \frac{\partial A}{\partial t} \right\} + \frac{\nu}{2} (B_{rx} [c_i] - B_{ry} [b_i]) \quad (9)$$

Galerkin's form of the stator winding equation (3) is

$$V_s = \frac{l}{s} \left[\iint_{\Omega^+} N_i \frac{\partial A}{\partial t} d\Omega - \iint_{\Omega^-} N_i \frac{\partial A}{\partial t} d\Omega \right] + R i + L_\sigma \frac{di_s}{dt}, \quad (10)$$

and its matrix form is,

$$V_s = \frac{l}{s} \left[\left\{ Q \right\} \left\{ \frac{\partial A}{\partial t} \right\} \right]_{\Omega^+} - \left\{ Q \right\} \left\{ \frac{\partial A}{\partial t} \right\} \right]_{\Omega^-} + R i_s + L_\sigma \frac{di_s}{dt} \quad (11)$$

For the above equations,

$$G = \iint \left(\frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} \right) dx dy = \frac{b_i b_j + c_i c_j}{4\Delta_e}, \quad (12)$$

$$T_{ij} = \iint N_i N_j dx dy = \begin{cases} \Delta_e/6 & i = j \\ \Delta_e/12 & i \neq j \end{cases}, \quad (13)$$

$$Q = \iint N_i dx dy = \frac{\Delta_e}{3}, \quad (14)$$

Where, Δ_e is the triangular area of the element.

Time dependent field equation, circuit equations and rotor motion equation are discretized in time domain by time stepping method that consists of implicit or explicit time integration procedures. Backward Euler's method is used in this work. The method can be represented by the following equation,

$$\left\{ \frac{\partial A}{\partial t} \right\}^{t+\Delta t} = \frac{\{A\}^{t+\Delta t} - \{A\}^t}{\Delta t} \quad (15)$$

Hence, the stator conductor field equation after time discretization can be represented as

$$\nu [G] [\Delta A]^{t+\Delta t} + \frac{[Q]}{S} [\Delta I]^{t+\Delta t} = 0, \quad (16)$$

and the field equations of the iron core and permanent magnet after time discretization are

$$\frac{\sigma [T] \{A\}^{t+\Delta t}}{\Delta t} + \nu [G] \{A\}^{t+\Delta t} = \frac{\sigma [T] \{A\}^t}{\Delta t} \quad (17)$$

and

$$\nu [G] [\Delta A]^{t+\Delta t} + \frac{\nu}{2} (B_{rx} [c_i] - B_{ry} [b_i]) = 0. \quad (18)$$

The stator phase circuit equation after time discretization can be described as

$$\frac{l}{s} \{Q\} \left(\frac{\{A\}^{t+\Delta t} - \{A\}^t}{\Delta t} \right)_{\Omega^+} - \frac{l}{s} \{Q\} \left(\frac{\{A\}^{t+\Delta t} - \{A\}^t}{\Delta t} \right)_{\Omega^-} + L_\sigma \frac{\{i_s\}^{t+\Delta t} - \{i_s\}^t}{\Delta t} = V_s - R i_s^{t+\Delta t} \quad (19)$$

The external circuit equation and the rotor movement equation after time discretization can be expressed as

$$\left\{ [R_{sb}] + \frac{[L_{sb}]}{\Delta t} \right\} [i_{sb}]^{t+\Delta t} + \frac{[C_{sb}]}{\Delta t} [V_{sb}; V_t]^{t+\Delta t} = \frac{[L_{sb}]}{\Delta t} [i_{sb}]^t + \frac{[C_{sb}]}{\Delta t} [V_{sb}; V_t]^t \quad (20)$$

and

$$J \frac{\omega^{t+\Delta t} - \omega^t}{\Delta t} = T_e - T_f - B\omega. \quad (21)$$

In this model, field equations of iron core are nonlinear due to the presence of ferromagnetic materials. Linearization of these equations is required before they combined with final global matrix equations. Newton-Raphson procedure is applied to linearize the nonlinear equations. Then, final global system of equations is assembled and solve simultaneously. At each iteration cycle, the Incomplete Cholesky Conjugate Gradient (ICCG) algorithm is used to solve the global system of equations. The magnetic vector potential A and stator phase current i_s are calculated directly from the solutions of global system of equations at each time step. From which required field parameters and motor performances such as speed, torque, force, rotor positions in time domain are calculated. ****

IV. COUPLING THE ROTOR MOVEMENT WITH FE MODEL

Using FEM to calculate the field problem in time domain, rotor mesh should be simple, robust and allowed to rotate easily. In this work, simple and reliable moving mesh technique [9] is adopted in simulation of rotor rotation. The FEM mesh of the spindle motor is divided into two parts: stator and rotor with each containing air gap. Air gap is divided into three layers as shown in Fig. 3.

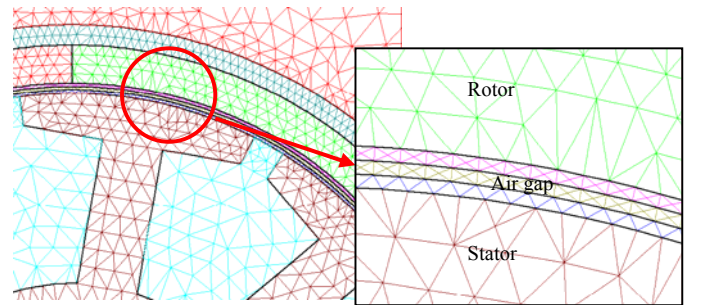


Fig. 3 Air gap is divided into three layers

The outer two layers are assigned to the rotor and these are rotated together with the rotor while the inner layer is assigned to the stator and is kept fixed. The innermost nodes of the rotor

mesh and the outermost nodes of the stator mesh are connected by the periodic boundary condition. When the rotor is rotated according to the time step, the shape of the mesh for both rotor and stator can be kept constant and only the coordinates of the rotor mesh and periodic boundary condition on the interface are needed to change. Rotor displacement at each time step is calculated from the rotor motion equation as follows.

After time discretization, speed is determined from the motion equation (18)

$$\omega' = \omega^{t+\Delta t} + \left(\frac{T_e - T_L}{J} \right) \times \Delta t, \quad (22)$$

where electromagnetic torque T_e is calculated by the Maxwell Stress Tensor method based on FEM solution. Define $\Delta\theta = \omega' \times \Delta t$, the rotor displacement at each time step can be determined by

$$\theta' = \theta^{t+\Delta t} + \Delta\theta, \quad (23)$$

V. COUPLING THE CONTROL LOOP WITH FEM

In the hard disk drive system, fast and accurate control of disk spinning speed is vital for error free read and write operations. This requires a sophisticated controller for the purpose of rapid response. In this model, a simple and cascaded speed and current control structure, based on the current hysteresis PWM switching strategy is proposed to couple the time stepping FEM model. Detailed control system block diagram is shown in Fig.4. In the control loop simulation, the required feedback signals, rotor speed ω and stator current I_s are determined from the FEM model. In the outer speed loop simulation, the reference speed ω^* is 7200 rpm where actual motor speed is calculated from the FEM model. In the inner current loop, reference current I_s^* for the current hysteresis loop is determined from the PI controller of the speed loop. The feedback current signal I_s is determined from the time stepping FEM model. The output of the current hysteresis loop is the firing signal α for the inverter circuit and again these are the input voltage for the FEM model.

Detailed modeling technique for current hysteresis control is as follows. The reference current is determined by the PI controller of the speed loop;

$$I_s^* = \begin{cases} K_p(\omega^* - \omega) + I_k^* & , \quad -I_m \leq I_s^* \leq I_m \\ I_m & , \quad I_s^* > I_m \\ -I_m & , \quad I_s^* < -I_m \end{cases}, \quad (24)$$

where,

$$\begin{cases} I_0^* = 0 \\ I_k^* = I_{k-1}^* + \frac{\omega^* - \omega}{T_s} \Delta T \end{cases}. \quad (25)$$

Therefore, the reference current is $i_s^* = I_s^* i^*$. In (21), K_p is the proportionality factor, T_s is the integral factor; ΔT is the time step size; I_m is the maximum allowable value of stator current and i^* the expected current waveform with just unity value of 0 and 1. Finally, the stator voltage is controlled by the following current loop when $i_s^* \neq 0$,

$$V_{s(k)} = \begin{cases} +V_s & i_s < i_s^* - \Delta i \\ -V_s & i_s < i_s^* + \Delta i \\ V_{s(k-1)} & i_s^* - \Delta i \leq i_s \leq i_s^* + \Delta i \end{cases}, \quad (26)$$

By coupling the closed loop speed and current control with the FEM, the stator windings could be fed with the actual output voltage from the inverter to FEM model. In addition, motor performance under transient conditions can be controlled instantaneously as an actual motor-controller system.

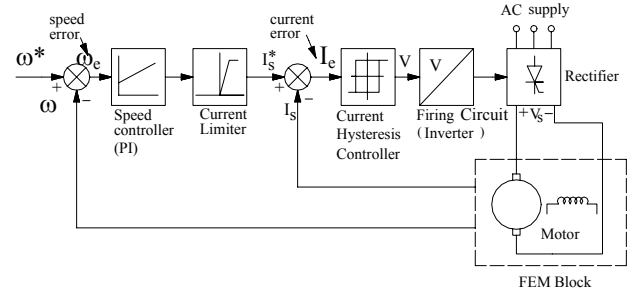


Fig. 4 Control system block diagram

VI. RESULTS AND DISCUSSIONS

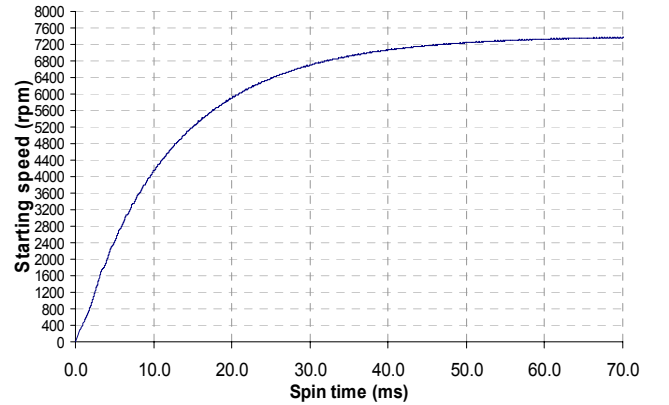


Fig. 5 Motor spin up time to reach the rated speed without any limits

The proposed model is validated and used to investigate the starting performances of a 3.5 inch HDD spindle motor. Motor specifications are listed in Table-I. Starting performances of the motor with and without the drive limits at no load and loaded conditions are analyzed. In this simulation, motor terminal voltage is 8V. Fig. 5 shows the rotor operation in the

starting period without any drive limits under no load condition. In this period, both the drive current and EM torque vary rapidly; see Fig. 7 and Fig. 6. Since the motor is started without any limits for maximum acceleration, it can spin up in 50ms to reach the rated speed of 7200rpm. Motor starting torque can be as high as 33.5mNm where starting current is unlimited and goes up to 3.36A as shown in Fig. 7 and Fig. 6.

TABLE -I MOTOR SPECIFICATIONS

Rotor outer diameter	33mm
Rotor inner diameter	28.5mm
Stator outer diameter	25.1mm
Magnet thickness	1.55mm
Air gap thickness	0.2mm
Magnet remanence flux density, Br	0.7T

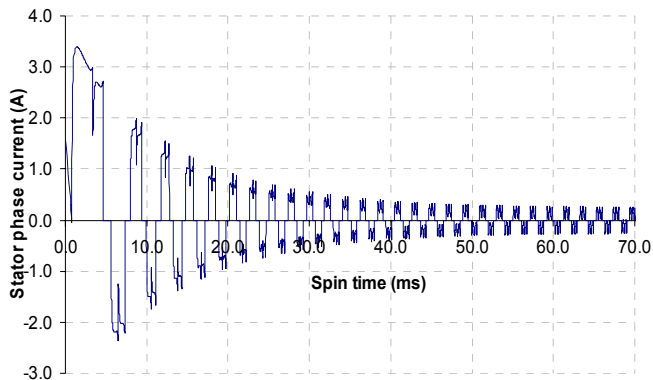


Fig. 6 Motor starting current without any limits

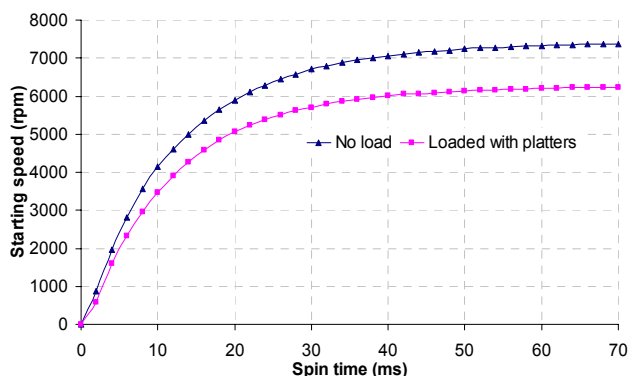


Fig. 8 Comparison of spin up time with no load and loaded with platters

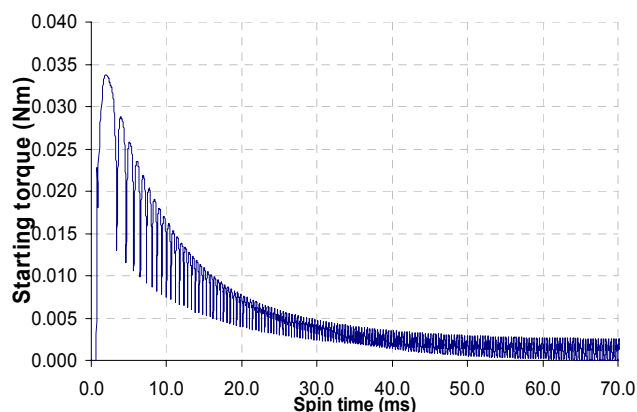


Fig. 7 Motor starting torque without any limits

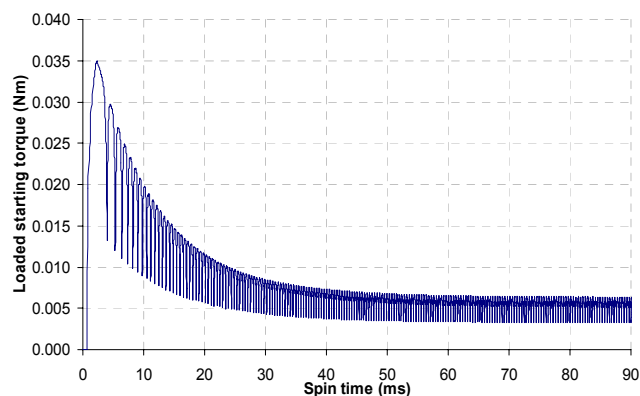


Fig. 9 Motor starting torque profile loaded with platters

Spindle motor is required to spin one or several disk platters according to the design of HDD. The starting characteristics of motor loaded with 3.5 inch platters are analyzed in this work. Moment of inertia of the platter is added to the rotor motion equation (5) and then the motor performance is simulated. The starting speed against spin up time for no-load and loaded with platters is shown in Fig. 8. Motor speed cannot reach to its rated speed when loaded with platters at the same voltage level. Starting torque also goes up to 33.5mNm in loaded with platters, as shown in Fig. 9. In this period, the starting current can be 3.45 A; see Fig. 10. In real application, the number and the size of the platters vary in different hard disk designs. The trend of the hard disk drive is towards smaller platter sizes to reduce the windage loss in the plate operation, and the drive performance and reliability can also thus be improved.

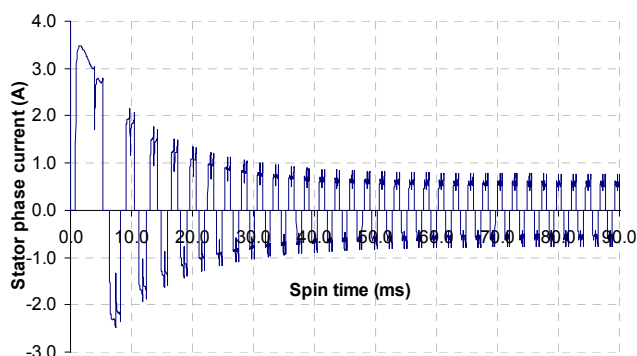


Fig. 10 Motor starting current against spin time when loaded with platters

Generally, in HDD operation, 25% of 12V PC power supply is taken by the actuator assembly and the rest 75% can be taken by the spindle motor [10]. Hence, in practical case,

motor current is limited by the computer power supply. Therefore, the starting motor with 1.8A current limit is simulated. Since, starting current is limited as shown in Fig. 11, motor starting torque cannot be as high as previous case where there is no limitation to the drive current. The spin up time is thus slower; see Fig. 12 and Fig. 13. To increase the starting torque and faster the spin-up time with the current limitation, the optimization to the EM structure of the spindle motor and drive circuit is important.

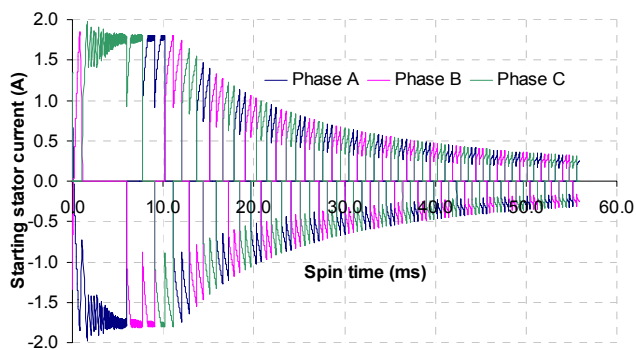


Fig. 11 Starting current with 1.8A current limiter

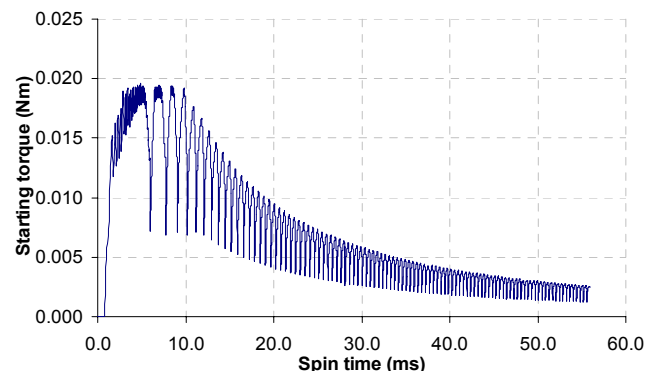


Fig. 12 Motor starting torque with 1.8A current limit

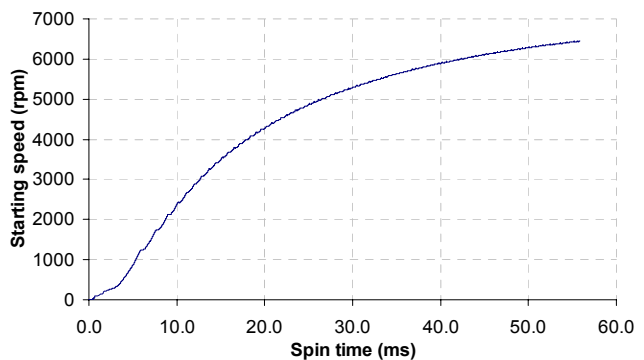


Fig. 13 Motor starting speed with 1.8A current limit

VII. CONCLUSIONS

When a motor is used to spin a spindle system, the analysis for its transient performance becomes very difficult, especially

when the problem becomes a coupling one where both the effects of external drive circuit and mechanical characteristics of the spindle system are considered. The paper presents a model for analyzing such a coupling problem. The detailed equations are given in the paper, and the starting performance of a spindle system is analyzed with the model. From the analysis results obtained, the model presented can work satisfactorily when it is used in simulation for real cases where the drive limits are considered. Though the model is based on the analysis to the permanent magnet synchronous motor used in hard disk drive, it can be easily extended to analyze the other drive systems to evaluate the starting characteristics and transient performances of the systems as well.

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