Dynamic Braking Optimization for Reducing Demagnetization Phenomenon during Fast Stopping in AFPM Motor

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Abstract: *A type of electrical machine geometry is the axial flux permanent magnet (AFPM) machine which has a significant role in industrial applications because of high torque/power density. In these motors, it takes about 10 second to normally stop when working at full load condition and rated speed. In emergency situations, some can perform a crash stop maneuver, which can cut the time down to 0.3 second. For AFPM motor, dynamic braking is easily achieved by cut off motor from main supply and shorting the motor terminals, thus bringing the motor to a fast abrupt stop. But as three phase armature winding are short circuited, a high instantaneous current flow through the stator winding. These peak values of current generate a high armature reaction field that extremely demagnetizes PMs. To solve this problem, the armature terminals are short circuited by means of a current limiting resistor. Then the ohmic value of this optimum resistor is calculated to reduce the three phase short circuit demagnetization and the motor stops in less than 0.52 second.*

Key words: *Axial Flux Permanent Magnet motor; Current limiting resistor; Dynamic braking; Irreversible demagnetization; Three-demential Finite element;*

I. INTRODUCTION

A type of electrical machine geometry is the axial flux machine, where the magnetic field runs axially across the air gap. Since the 1980s, accelerated by the availability of powerful new neodymium iron-boron (NdFeB) permanent magnets, research on axial flux permanent magnet machines has increased. Because of their high torque-to-weight ratio and compact flat shape, AFPM machine became significant in industrial applications [1].

One of the application modes for these motors is braking. For AFPM motor, dynamic braking is easily achieved by cut off motor from main supply and shorting the motor terminals, thus bringing the motor to a fast abrupt stop. But the armature current following a sudden-three-phase short circuit has high instantaneous peak values that extremely demagnetize PMs [2], [3]. Several authors have studied the fast stopping of a PM machine. However, the dynamic braking has not been studied from the point of demagnetization phenomenon.

This paper presents a method for reducing irreversible demagnetization during dynamic braking. In this study, by using the dynamic model of AFPM and the transient analysis, motor performance was calculated in braking condition. Then finite element analysis has performed and the percentage of demagnetization in PMs is considered. As a final point, an optimized fast stopping is proposed that can effectively reduce irreversible demagnetization effect.

II. DYNAMIC BRAKING

In some emergency situation, abrupt stopping of the electric drives is necessary. In this mode of operation, a braking torque is created by the interaction of a constant magnetic flux in an electric motor with magnetic flux produced by the current of short circuiting the armature winding.

The armature current variation of the synchronous machine following a sudden-three-phase short circuit is described by the following expression [4].

$$i_a(t) = I_{ac}(t)\sin(\omega_r t + \lambda) - I_h(t)\sin(2\omega_r t + \lambda) - I_{dc}(t)\sin\lambda$$

where

$$I_{ac}(t) = V_o\sqrt{2}\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{-\frac{t}{T'_d}} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{-\frac{t}{T''_d}}\right] \quad (1)$$

$$I_{dc}(t) = \frac{V_o}{\sqrt{2}}\left(\frac{1}{X''_d} + \frac{1}{X''_q}\right)e^{-\frac{t}{T_a}}$$

and

$$I_h(t) = \frac{V_o}{\sqrt{2}}\left(\frac{1}{X''_d} - \frac{1}{X''_q}\right)e^{-\frac{t}{T_a}}$$

ω_r : The machine rotor speed (radians/seconds)

$V_o\sqrt{2}$: The peak pre-fault value of the terminal voltage in per unit

The short circuit currents in the three phases during short circuit are as shown in the Fig. 1 [4], [5].

It is important that the peak braking power be compared to that of the rated motor power. If the peak braking power is greater than that of the motor, then the deceleration time needs to be increased so that the motor does not go into thermal limit. The peak braking power is calculated by the following expression [6], [7], [8].

$$P_b = \frac{KE}{t_d} = \frac{0.5 \times J_T \times \omega_{rated} (\omega_{rated} - \omega_{stop})}{t_d} \quad (2)$$

Where

KE= kinetic energy

J_T = total inertia reflected to the motor shaft (kg. m^2)

ω_{rated} =rated angular rotational speed (rad/sec)

ω_{stop} =0 (rad/sec)

t_d =time of deceleration from ω_{rated} to ω_{stop}

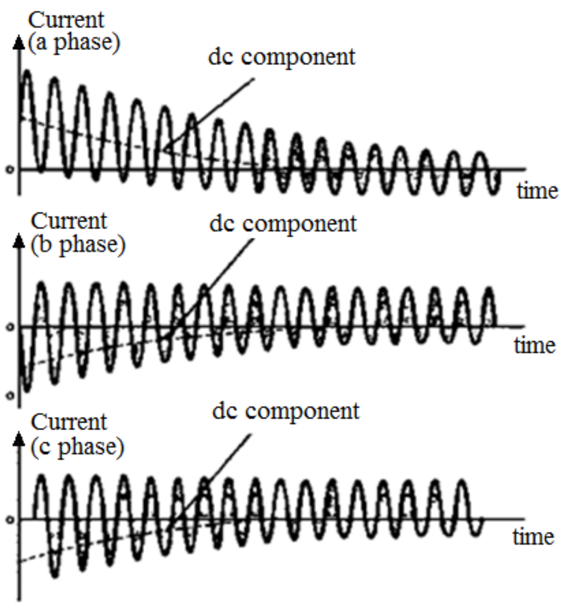

Fig. 1 Short circuit current waveforms in the three phases of machine.

Consider Fig. 1, the stator winding has large instantaneous peak values. These peak values of current generate a high armature reaction field that may demagnetize motor PMs. So it seems necessary to investigate the possibility of demagnetization occurrence and its effect on motor performance.

III. DEMAGNETIZATION PHENOMENON

When permanent magnet machine subjected to armature reaction magnetic field, the magnetic properties of permanent magnets may change, leading to demagnetization. The second quadrant of the hysteresis curve of the magnetic material referred to as the demagnetization curve. Each of the demagnetization curves has a bend in it, mentioned as the "knee". The Knee gets higher with increasing temperatures. If the magnet load line crosses above the knee in the curve, then the magnet is operating in its safe linear region. But if the magnets are operated below the knee, irreversible change takes place and the magnet cannot recover its original magnetization even when brought back to the initial condition. After removing the demagnetization factor, the operating point will move along the recoil curve. The recoil is in parallel with the tangential line to the B-H curve H=0 and B= B_r [9], [10]. The reduction of the residual flux density of the PM, after the external demagnetizing field is removed, called irreversible demagnetization, as in (3).

$$\text{Demagnetization Ratio} = (1 - \frac{B_{r-new}}{B_r}) \times 100 \quad (3)$$

B_{r-new} : Residual flux density after demagnetization occurred.

B_r : Residual flux density before demagnetization occurred.

An example of the demagnetization curve of a PM is shown in Fig. 2.

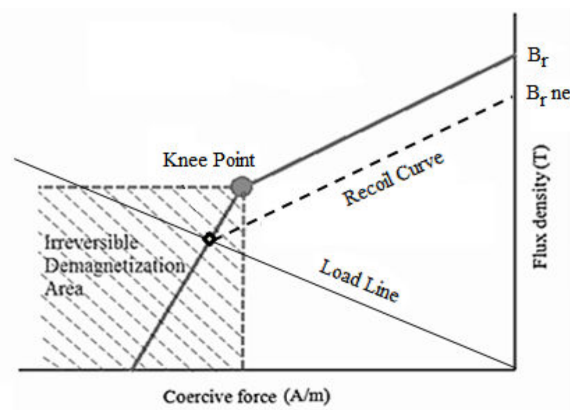

Fig. 2 Demagnetization curve

IV. MOTOR STRUCTURE OF CASE STUDY

To study demagnetization phenomenon on AFPM motors, consider a 22-pole non-slotted permanent magnet TORUS kind one with disc-type rotor. The structure of motor and its dimensions are shown in Fig. 3 and Fig. 4 respectively. Such motors are of interest in high torque and low speed applications [11]. The permanent magnets of this motor are made of Neodymium Iron Boron. Its material demagnetization characteristic was shown in Fig. 5. The main model parameters were also presented in Table I [12]. It is seen that the motor effectively comprises two independent halves, lying either side of the radial centerline. Because of symmetry condition only half part of motor was simulated [11].

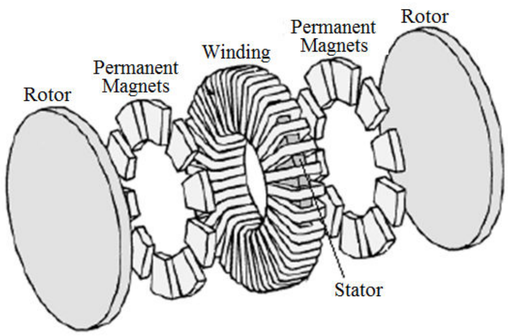

Fig. 3 Components of an Axial Flux Permanent Magnet motor [12].

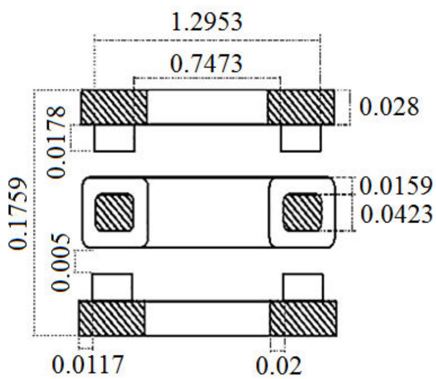

Fig. 4 Dimensions of the AFPM motor in meters.

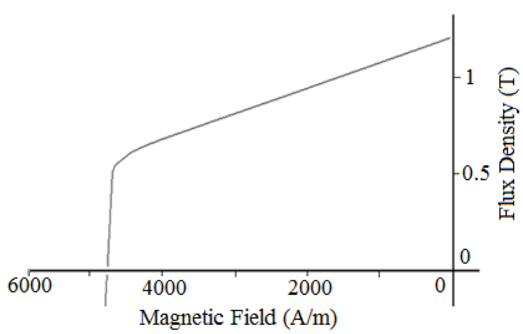

Fig. 5 Demagnetization curve of NEOMAX-42 (100 °c).

Table 1
Motor specification

Item	Value	Unit
Number of poles	22	
efficiency	0.95	
Nominal Power	0.5	Mw
Rotation Speed	300	rpm
frequency	55	Hz

As shown in Fig. 6, in these motors, it takes about 10 second to normally stop[1] when working at full load condition and rated speed.

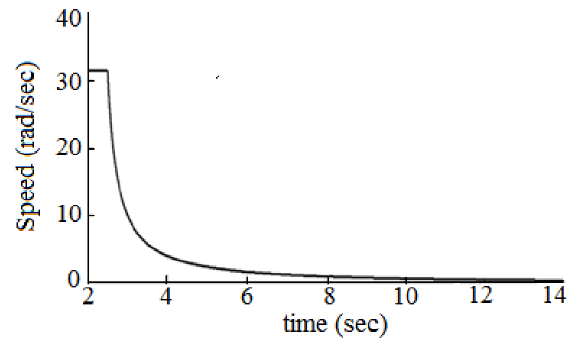

Fig. 6 Cut off motor from main supply at time of 2.5^{th} second.

V. FINITE ELEMENT SIMULATION

Modeling of electrical machines is very significant because it is used in study of machines performance. Three dimensional finite-element method (FEM) allows an accurate analysis. So, it is an appropriate method for analyzing AFPM machines. Finite element method is based on Maxwell's equations. The FEM-based study of irreversible demagnetization is done in peak values of current curves and instantaneous rotor positions condition.

A. Irreversible Demagnetization Analysis Method

The resulting dynamic model is used to perform a transient analysis of the AFPM motor including the determination of the instantaneous motor phase currents and rotor positions. Then, finite element method (FEM) is used for the magnetic field analysis. By using magneto-transient analysis, the flux density and magnetic field strength distribution over the model is obtained. When the operating point of PM is below its knee point, the residual flux density of the PM is renewed in the analysis process. The knee point of the magnet used for the analysis is 0.52 T. By comparing results before and after demagnetization analysis field, irreversible demagnetization of PM is determined. The process of the irreversible demagnetization analysis of AFPM motor is presented in Fig.7.

B. Fast stopping condition

Assume that at full load condition, at time of 2.5^{th} sec, a three phase short circuit is occurred in armature winding. In this situation consider Fig. 8, the stator winding has large instantaneous peak values. These peak values of current generate a high armature reaction field that may demagnetize motor PMs. The mechanical speed variation in this state is indicated in Fig. 9.

1: Normally stop is achieved by cut off motor from main supply.

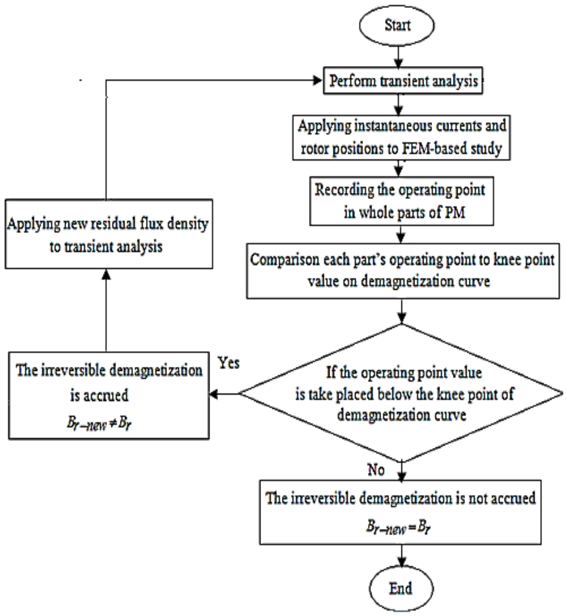

Fig.7 Demagnetization analysis process.

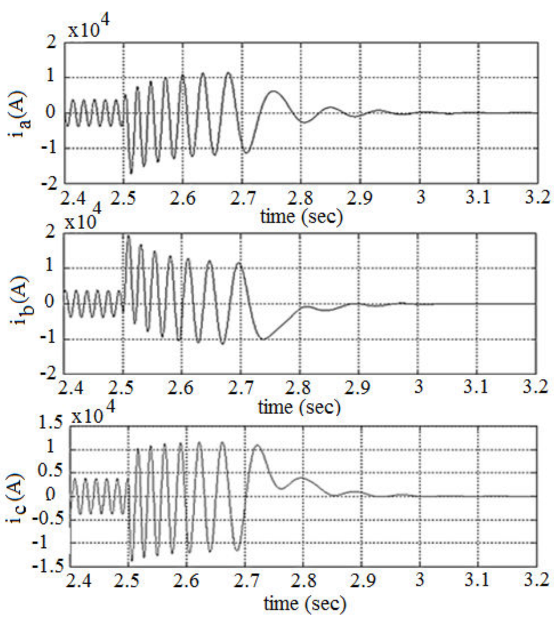

Fig. 8 Short circuit current waveforms in the three phases of AFPM without dynamiv braking resistance.

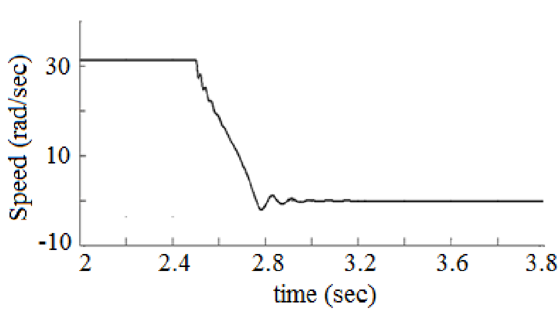

Fig. 9 Rotor mechanical speed

These currents and are applied to FEM-based analysis and motor magnetic conditions are obtained. The flux density distribution is shown in Fig.10. Consider Fig.10, the orientation of PM magnetization and the direction of armature reaction flux in some part of magnet is opposite. So the flux density value of those parts is reduced. But in other parts that the direction of the leakage flux is in the same PM magnetization orientation, the PM flux density is strengthened. In some part of magnet, the value of the flux density in the PM takes its place below the knee point of demagnetization curve, and the magnet is demagnetized irreversibly.

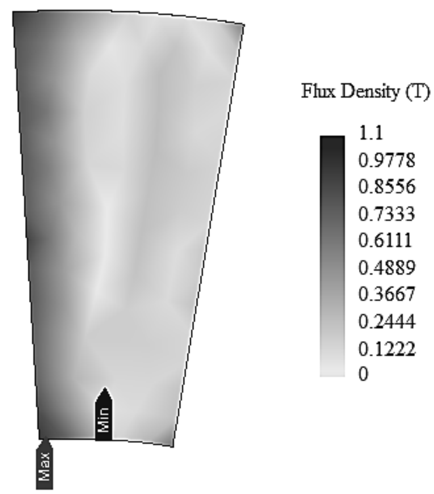

Fig. 10 Flux density contour plot of the magnets at time of 0.0045th sec in three phase short circuit condition.

VI. RESULT AND DISCUSSION

After removing the demagnetization factor, the operating point will move along the recoil curve. In this case, the residual flux density changes. Because of extreme armature reaction, the demagnetization ratio is high. The analysis results of irreversible demagnetization are presented in table 2. The lowest operating point in PM is shown in Fig. 11.

Table 2
Demagnetization ratio

Item (%)	Three Phase Short Circuit
Demagnetized area in PM	72.38
Demagnetization ratio	19.18

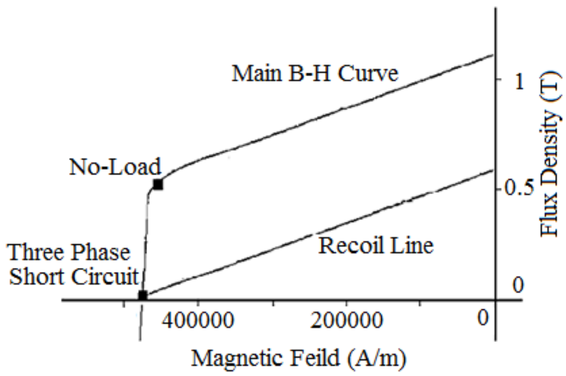

Fig. 11 The lowest operating point in PM (100 °c).

As shown, the high current flow through the short circuited stator winding, extremely demagnetized PMs. To solve this problem, a current limiting resistor placed across the armature terminals and the stator winding is short circuited by means of this resistor. In this way, not only peak values of short circuit current are reduced but also the motor can stops as soon as possible.

VII. SELECTING DYNAMIC BRAKING RESISTOR

Consider equation (2), the peak braking power is determined.

In this AFPM motor, J_T is about 126.96 kg. m^2. For time of deceleration less than 0.52 sec we have:

P_b =0.2409 MW

Note that this is 22.49 % of rated power and is less than the maximum thermal limit. This peak power must be dissipated by the dynamic braking resistor. Following equation determines the maximum ohmic value of the dynamic brake resistor [13].

$$R_{b\max} = \frac{V_{dc}^{\;2}}{P_b} \qquad \text{(ohm)} \qquad (4)$$

Where

V_{dc} = The value of DC Bus voltage

For 0.5 MW AFPM motor with DC Bus voltage of 220 volt, $R_{b\max}$ is calculated to 0.2009 ohm (7.52 per unit). The choice of the dynamic braking resistance value should be less than $R_{b\max}$.

VIII. OPTIMIZATION DYNAMIC BRAKING FOR REDUCING THREE PHASE SHORT CIRCUITED DEMAGNETIZATION

To investigate the ohmic value of optimum braking resistor, the demagnetization ratio was recorded for different resistors. It was found that there is a relationship between irreversible demagnetization ratio and braking resistor. This relationship follows an approximately 3 degree polynomial-type curve. This approximation is based on simple curve fitting to experimental data. Moreover, the stopping time of motor during short circuiting also depends on value of this resistance as shown in Fig 12.

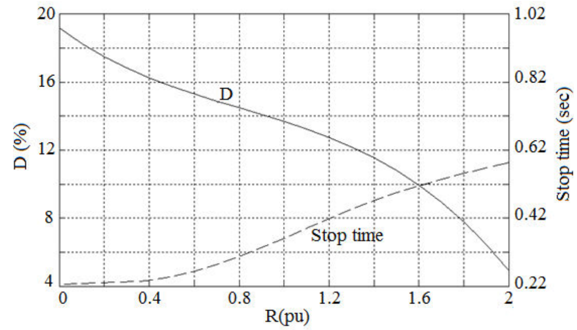

Fig.12 Average irreversible demagnetization ratio-braking resistance and stopping time-braking resistance graph.

For 1.6 per unit resistance, as shown in Fig 13 and Fig 14, the peak values of short circuit current are reduced, and the motor stops in less than 0.52 second.

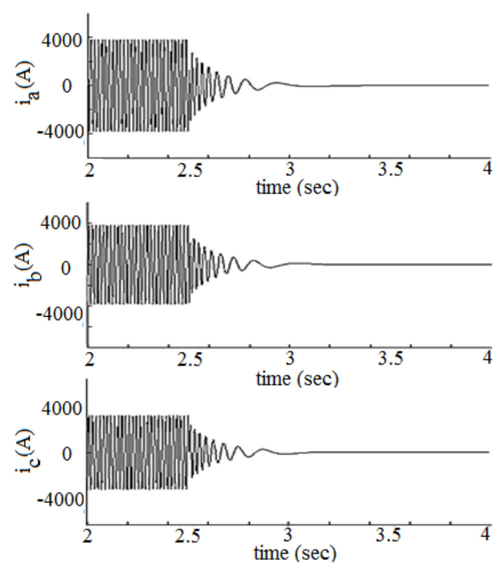

Fig.13 Short circuit current waveforms in the three phases by adding dynamic braking resistor.

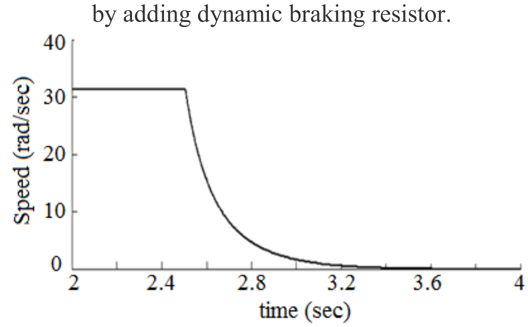

Fig.14 Cutting line power and shorting the motor terminals by a 1.6 pu resistance at time of 2^{th} second.

The effect of adding dynamic braking resistor on the PM demagnetization is evaluated by the FEA.

As seen in table, it is found that adding the resistor at motor terminals during the three phase short circuit are effective to reduce the PM demagnetization.

Table 3
Demagnetization ratio

Item (%)	Three Phase Short Circuiting Without resistance	Three Phase Short Circuiting By means of resistance
Demagnetized area in PM	72.38	60.424
Demagnetization ratio	19.18	9.954

IX. CONCLUSION

Dynamic braking in Axial Flux Permanent Magnet motor is easily achieved by cut off motor from main supply and shorting the motor terminals thus produced large current in stator winding. These peak values of current generate a high armature reaction field that demagnetizes motor PMs. In this paper, the study was performed on 0.5 MW AFPM motor, using the dynamic model of AFPM and the transient analysis and FEM. The irreversible demagnetization in the PMs produced by the armature reaction was evaluated. As results shown, the motor was affected by the external demagnetizing field because of large peak values of three phase short circuit current. This paper presents a method for reducing irreversible demagnetization during dynamic braking. In this method the armature terminals are short circuited by means of a resistor. The optimal value of dynamic braking resistor was tuned so that the three phase short circuit demagnetization reduced. From the finite element analysis results, the effectiveness of dynamic braking resistor in demagnetization reduction is confirmed. The irreversible demagnetization rate was reduced from 19.18% to 9.954%.

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