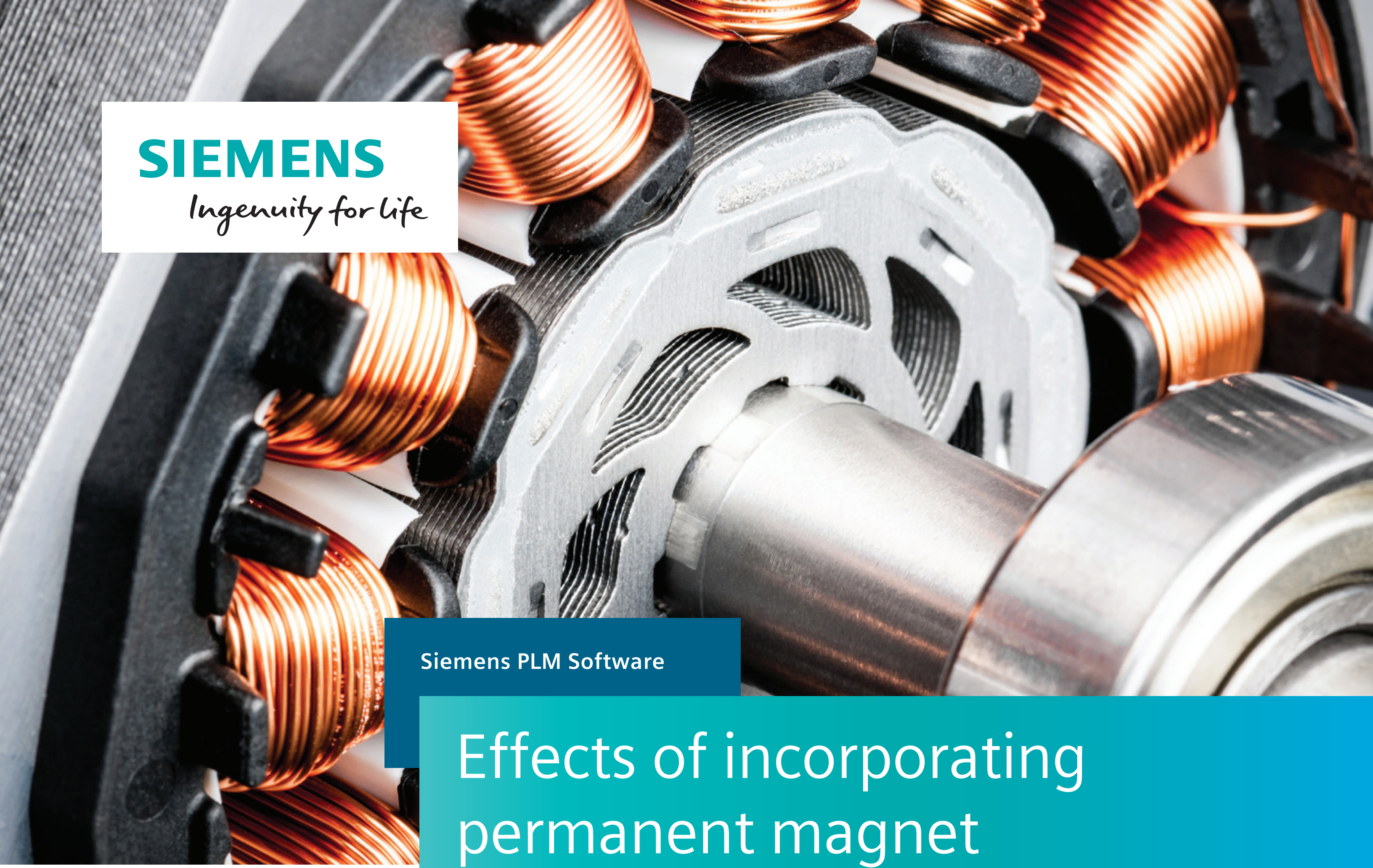

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Effects of incorporating permanent magnet demagnetization in the simulations of modern electric machines for electric vehicles

Executive summary

Modern electrical machines may face extreme operating conditions including high currents and temperatures which can lead to partial or complete demagnetization of the permanent magnets. For this purpose, a computationally efficient Demag model has been introduced in Simcenter MAGNET™ v7.9 software which includes temperature-dependence and maintains a history based on the magnetic field values. The model can be enabled with the 2D Transient solver (with or without motion).

The application of the Demag model in the simulation of the IPM machine demonstrates that the change in the PM's strength due to partial demagnetization can have drastic effects on the performance of the machine.

Sajid Hussain and Kang Chang

Introduction

Commercial software packages generally treat most permanent magnets as linear materials for various reasons including the ease of numerical implementation and the lack of measured data. There is a strong argument for such treatment. The BH curves of permanent magnets (PMs) such as NeFeB exhibit two almost linear sections joined by a sharp curve known as a knee point in the second quadrant of the BH plane [1]. One such curve for a NdFeB magnet (N42) material is shown in figure 1. Once the operating point moves past the knee point, the magnet is no longer considered good because it has lost its magnetization, and there is no point of using such a material in the design of an electrical machine if this behavior is not desired.

Alnico magnets, on the other hand, exhibit a smoothly varying behavior in the second quadrant and Simcenter MAGNET treats them as nonlinear permanent magnets and models the whole BH curve. Simcenter MAGNET can do so for other PM materials as well if the whole BH curve is available. Nevertheless, the magnetization in all cases is considered to be reversible, i.e., the magnet will regain its strength once it goes past the knee point and returns. In reality, the strength of the magnet degrades at a drastic rate beyond the knee point, and if it is to return, a new branch on the BH plane, known as the recoil line, is followed which has a lower remanence, as shown in figure 2.

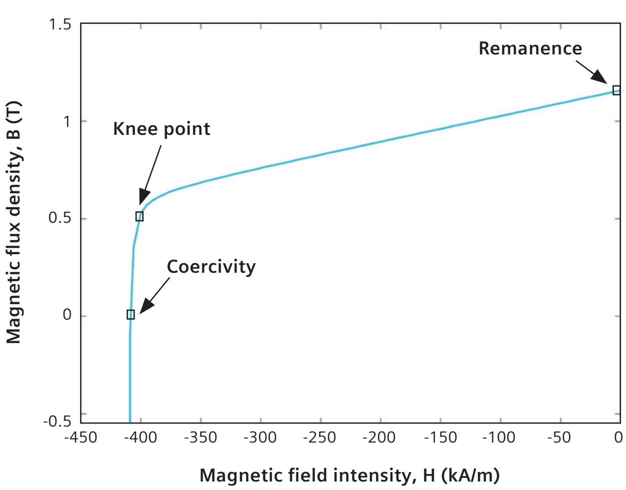


Figure 1: Measured Demagnetization BH curve of a high coercivity NeFeB magnet (N42) at 120 °C.

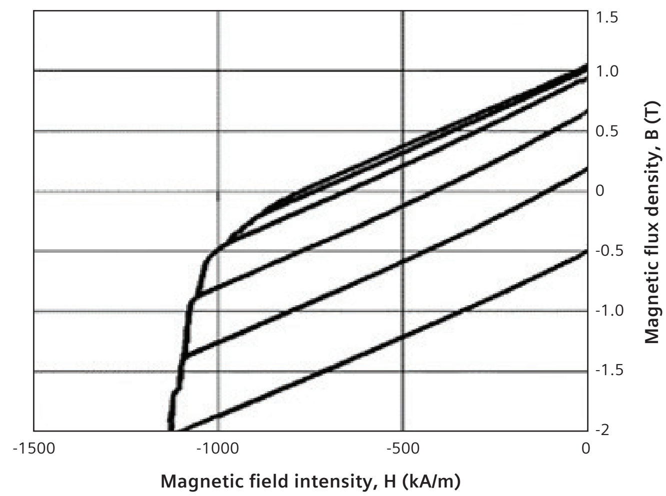


Figure 2: Measured recoil curves of a high coercivity NeFeB magnet at 120 °C [2].

Hysteresis models, such as that of Preisach, can represent the BH behavior of the PMs accurately by modelling the complete BH loop. However, these models require measured data in the first and third quadrant of the BH plane which is often not available in the case of PMs. For example, a decreasing branch of the major BH loop is required (at least) for the identification of the Preisach model, and such measurement will require specialized equipment which can apply very high magnetic fields, especially in the case of rare earth PMs (greater than 2000 kA/m). Moreover, the representation of a PM with a hysteresis model is redundant considering the user is mostly interested in the operation of the PM in the second quadrant only. Also, the hysteresis implementation will model minor loops with a significant loop area which is not generally observed in the measurements of PMs [2].

Incorporating demagnetization

The incorporation of the demagnetization of PMs in CAD simulations is important for the accurate prediction of device performance under fault or high-temperature conditions. Therefore, a temperature-dependent Demag model has been introduced in Simcenter MAGNET v7.9 which can predict the BH behavior of a PM in the second quadrant with reasonable accuracy and does not require additional material information. In fact, this model can be identified with three points only with a computational cost similar to the linear material model. The important characteristics of the PM, such as the linearized permeability and the knee point are derived from a nonlinear BH curve (as shown in figure 1) according to the MMPA standard [3] which means that the user doesn't need to provide demagnetization information.

Simcenter MAGNET by Siemens is a general-purpose 2D/3D electromagnetic field simulation software used for virtual prototyping of simple to complex electromagnetic and electromechanical devices. Using Simcenter MAGNET, engineers and scientists can design motors, sensors, transformers, actuators, solenoids or any component with permanent magnets or coils thus saving both time and money.

This paper focuses on the application of a new advanced feature of Simcenter MAGNET v7.9 which allows users to incorporate the demagnetization of the permanent magnets during a transient simulation using the temperature dependent Demag model [3]. The feature can be enabled when the simulation is solved using the Transient solver in 2D (with and without motion).

Application examples

In this section, two examples demonstrating the linear and the Demag models are presented. The first example of a simple cube PM demonstrates the working behavior of the Demag model whereas the second example is an interior permanent (IPM) magnet motor for electric vehicle applications. The results of the IPM motor will include a discussion on demagnetization fields, and its effects on global results, e.g. torque, etc., under a different scenario. Linear and Demag material models will also be compared.

1. A cube magnet surrounded by a current-driven coil

The first example demonstrates the irreversible behavior of the Demag model by demagnetizing a cube magnet (magnetized in the y-direction) surrounded by a current-driven coil. The Simcenter MAGNET model of this geometry is shown in figure 3 (a). The coil is excited by four cycles of sinusoidal current, as shown in figure 3 (b).

It can be seen in figure 4 that with every cycle of current, the PM's strength is decreasing because the amplitude of the current is large enough to push the magnetic fields beyond the knee point. The linear model of the PM does not show such behavior at all.

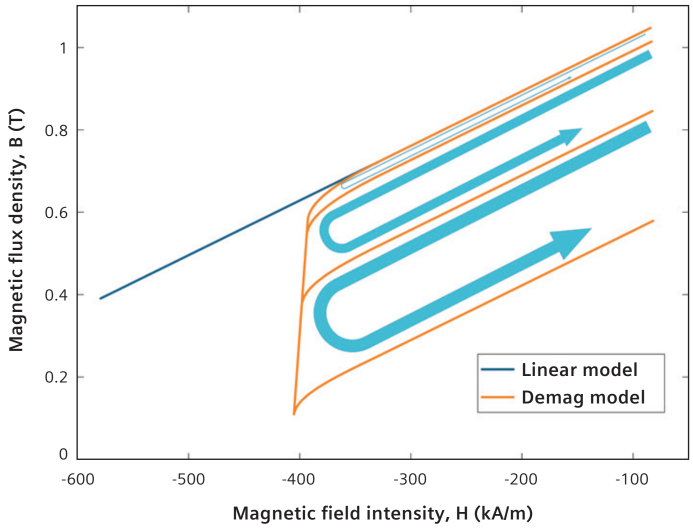


Figure 4: BH plot for an N42 permanent magnet using the linear and the Demag models in the magnetization direction.

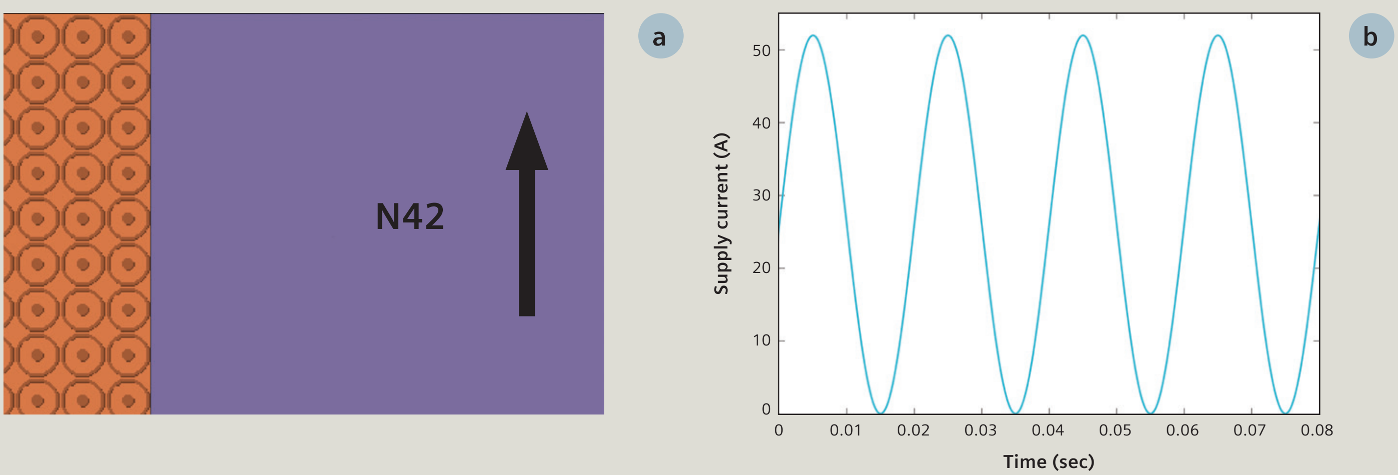


Figure 3: (a) Simcenter MAGNET model of a simple cube magnet surrounded by a coil, (b) the coil current.

2. An interior permanent magnet machine (similar to the Prius 2010)

A Simcenter MAGNET simulation of a current-driven interior permanent magnet (IPM) motor is presented here. The rated specifications of the test motor are provided in table 1. The machine is similar to the traction motor used in the Toyota Prius 2010.

The full Simcenter MAGNET model of a current-driven IPM motor is shown in figure 5. For simulation purposes, a 1/8 model was solved to simulate the following test cases for 5 supply cycles (frequency = 200 Hz) using the 2D Transient solver with motion. The permanent magnets in the IPM machine were modelled using both the linear and the Demag models, and the effects of incorporating demagnetization on torque are observed.

Table 1 – Machine specifications

Rater power	60 kW
Rated torque	220 N.m
Rated current	200 A
Frequency	200 Hz
Number of poles	8
Number of slots	48
Permanent magnet Material	N42 Recoil

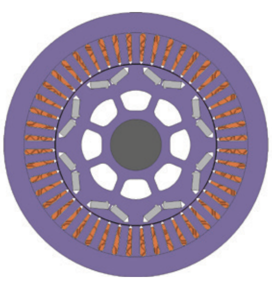


Figure 5: Simcenter MAGNET model of the IPM motor.

Test cases:

1. Demagnetization due to current loading at constant temperature (T = 120 °C)
2. Demagnetization due to the increase in temperature (from T = 120 °C to 150 °C)
3. Effect of demagnetization due to a short circuit on the back EMF in a Generator mode (T = 120 °C)

Test case 1: Demagnetization due to current loading at constant temperature

This test case is divided into three subcases depending upon how the current excitation is applied to the machine.

a. Start with low current (90 A) and then increase to high current (180 A)

b. Start with high current (180 A) and then decrease to low current (90 A)

c. Combine a and b

Subcase 1a

The three-phase current supply for subcase 1a is shown in figure 6 (a). The variation of the current can be divided into three stages, as shown in figure 6 (a). The first stage is a low current region. The second stage is a transition from low to high current and stage 3 is the high current region. The corresponding output torque of the machine using both the linear and the Demag model is presented in figure 6 (b). The torque in the low current (90 A) region is same for both models because the operating point is above the knee point. However, as the current increases, the PM goes into partial demagnetization and the torque computed using the Demag model is less than that from the linear model due to a loss of the PM's strength.

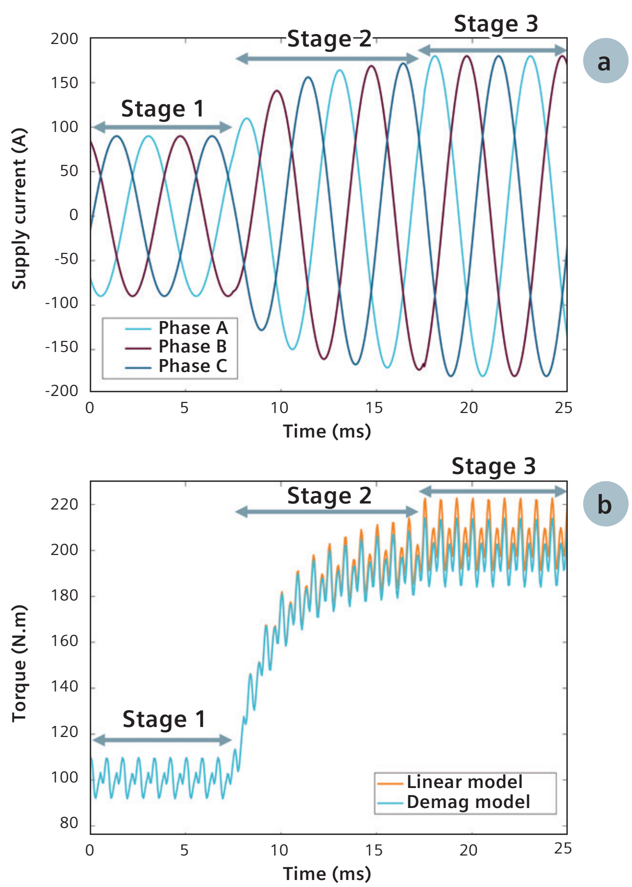


Figure 6: Test case 1a (a) Supply current (b) Torque using the linear and the Demag models.

The demagnetization proximity (defined by how far from the knee point the magnet has demagnetized) plots at t = 10 ms and t = 20 ms are shown in figures 7 (a) and (b), respectively. The BH field plot obtained using both the linear and the Demag models at a sample point in the PM demonstrating partial demagnetization is shown in figure 8.

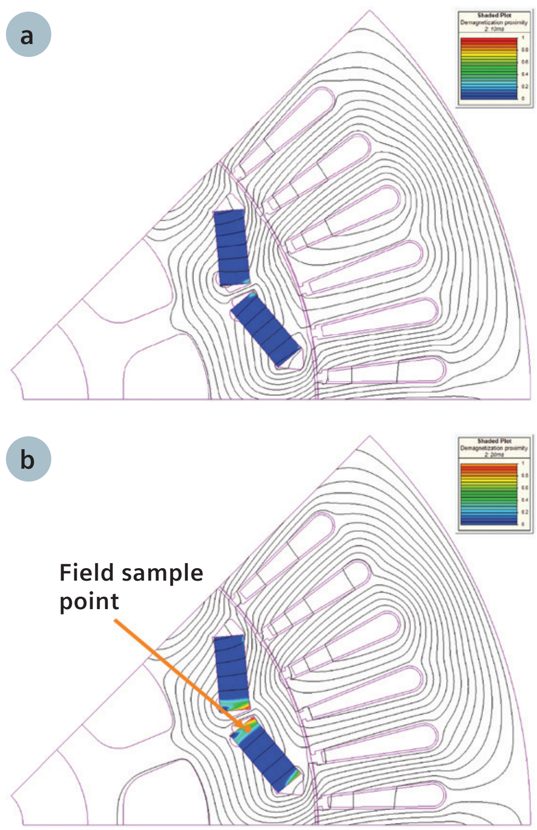


Figure 7: Demagnetization Proximity plots for N42 permanent magnet for (a) the linear model at 10 ms (b) the Demag model at 20 ms.

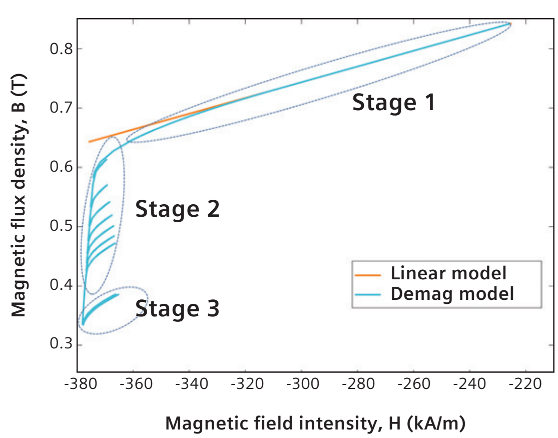


Figure 8: Test case 1a – BH plot of the N42 permanent magnet in the magnetization direction at a field sample point.

Subcase 1b

The three-phase current supply for subcase 1b is shown in figure 9 (a). The variation of the current can be divided into three stages, similar to subcase 1a, and is shown in figure 9 (a). The first stage is a high current region. The second stage is a transition from high to low current, and stage 3 is a low current region. The corresponding output torque of the machine using both the linear and the Demag model is plotted in figure 9 (b). The computed torques at high (180 A) and low (90 A) currents are different for both models because the PM has already suffered partial demagnetization which is shown by the demagnetization proximity plot in fihure 10 at t = 0 ms.

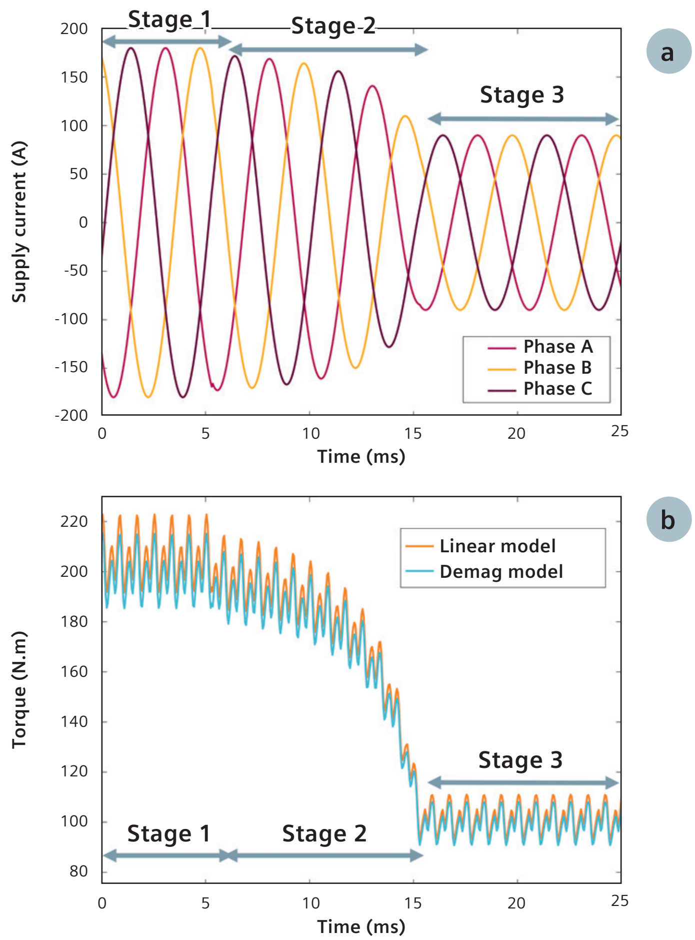


Figure 9: Test case 1b (a) Supply current (b) Torque using the linear and the Demag models.

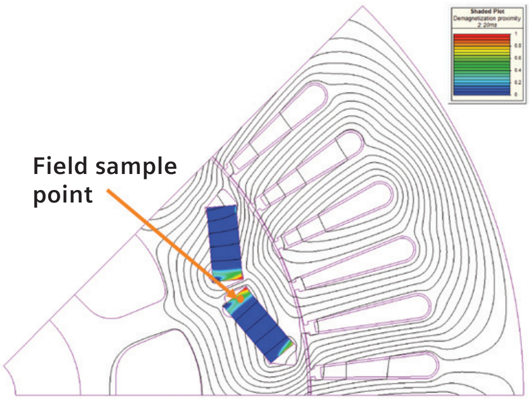


Figure 10: Demagnetization Proximity plot using the Demag model for the N42 permanent magnet at 0 ms at a field sample point.

The BH field plot obtained using both the linear and the Demag models at a sample point in the PM validating partial demagnetization at the beginning is shown in figure 11. The PM in this case never operates on the curve followed by the linear model.

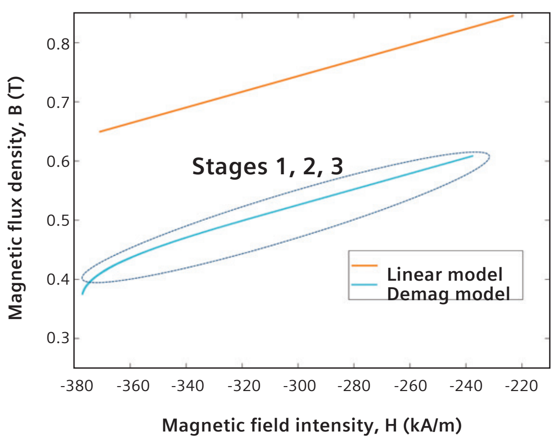


Figure 11: Test case 1b – BH plot for the N42 permanent magnet in the magnetization direction.

Subcase 1c

This test case is the combination of subcases 1a and 1b. The variation of the three-phase supply current can be divided into five stages, as shown in figure 12 (a). The current increases from low current (90 A) to high current (180 A) region and then reduces back to low current (90 A) region. The corresponding output torque of the machine using both the linear and the Demag model is presented in figure 12 (b). As in subcase 1a, the torque at low current (90 A) is same for both models. However, as the current increases, the PM goes into partial demagnetization and torque computed using the Demag model during stages 3 to 5 is less than that from the linear model due to a loss in PM's strength.

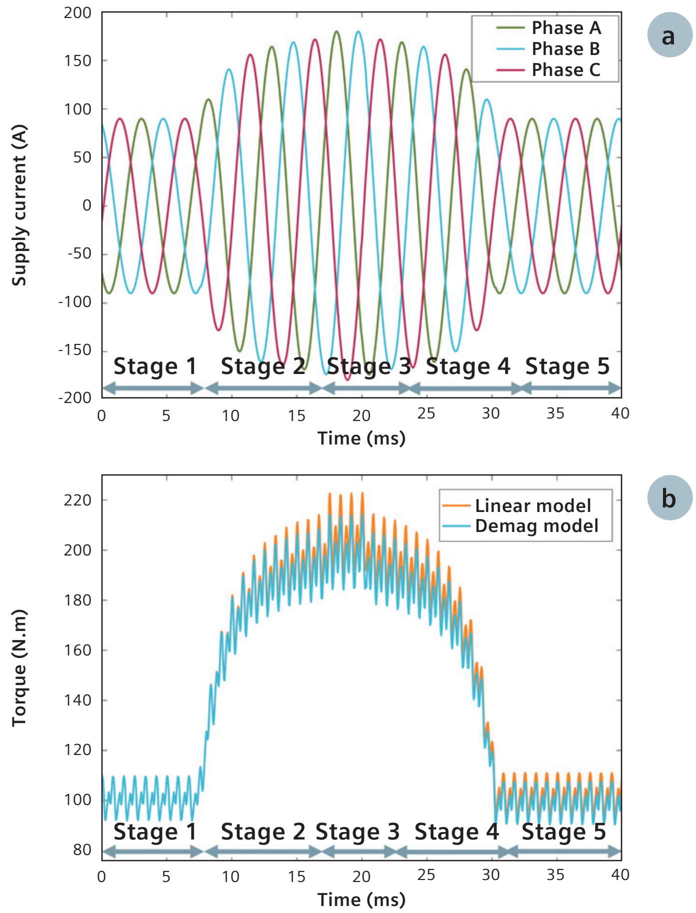


Figure 12: Test case 1c (a) Supply Current (b) Torque using the linear and the Demag models

The BH field plot obtained using both the linear and the Demag models at a sample point in the PM demonstrating the complete trajectory of the partial demagnetization is shown in figure 13.

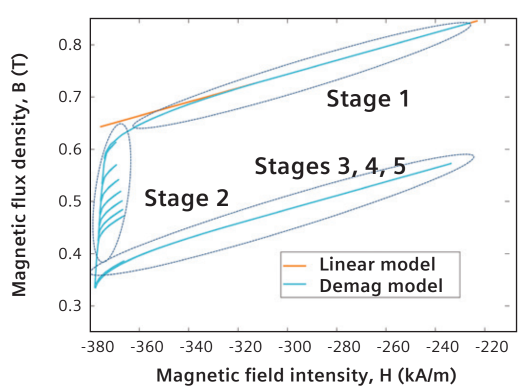


Figure 13: Test case 1c – BH plot for the N42 permanent magnet in the magnetization direction.

Test case 2: Demagnetization due to the increase in temperature

Figure 14 shows the measured BH curves of an N42 PM at two different temperatures, i.e., 120 °C and 150 °C. Test subcases 1a and 1b were simulated again at 150 °C, and the computed torques using both the linear and the Demag models are shown in figure 15. At elevated temperatures (due to a possible failure in the cooling system), the difference in the torques computed using the two models is large.

Figures 16 and 17 show the demagnetization shaded plots obtained for two temperatures at t = 10 ms and t = 20 ms for subcase 1a, respectively. It can be seen that elevated temperatures in the machine may cause complete demagnetization of the PM, as shown in figure 17 (b).

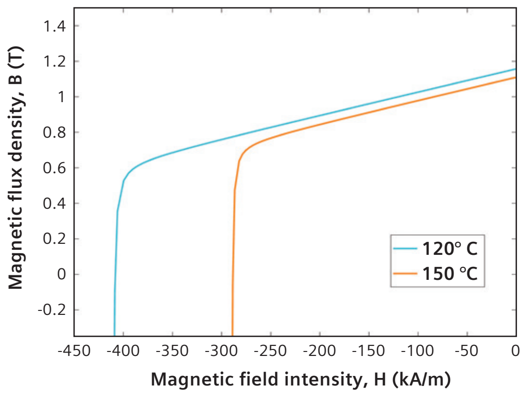


Figure 14: Measured demagnetization BH curves of the N42 permanent magnet at 120 °C and 150 °C.

Figure 16: Test case 1a – Sample Demagnetization Proximity plots for the N42 permanent magnet at 10 ms for (a) 120 °C (b) 150 °C.

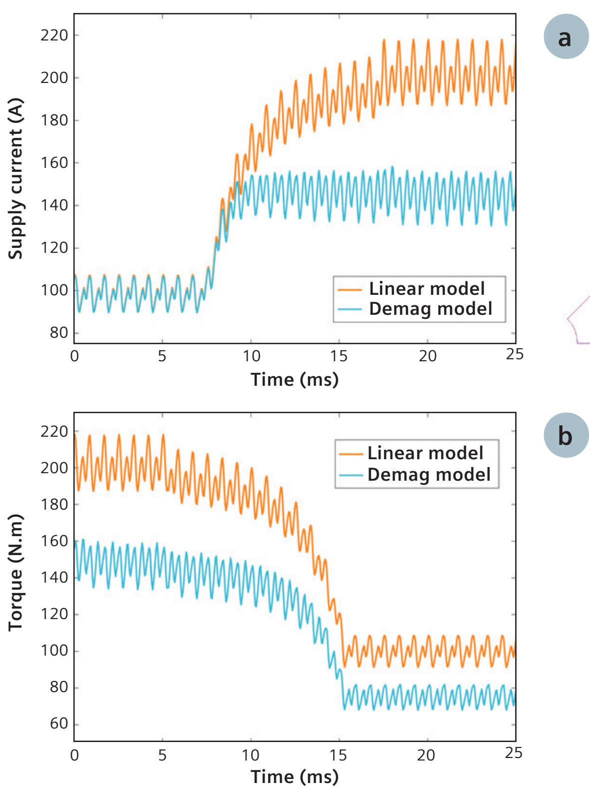


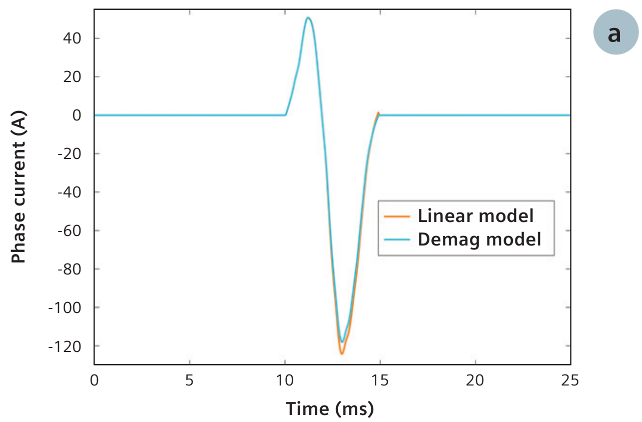
Figure 15: Test case 2 – Torques computed using the linear and the Demag models at 150 °C for (a) Test case 1a, and (b) Test case 1b.

Figure 17: Test case 1a – Demagnetization Proximity plots for the N42 permanent magnet at 20 ms for (a) the linear model at 120 °C (b) the Demag model 150 °C.

Test case 3: Demagnetization and its effects on back EMF due to short circuit

In this scenario, the IPM machine under test is run in generator mode. The three phases of the machine are connected in a Y-connection and are shorted together, i.e., the line to line voltage becomes zero at t = 10 ms, to simulate a short circuit, with the help of a circuit switch in Simcenter MAGNET. The short circuit will allow high currents to flow in all phases which can demagnetize a healthy magnet. At t = 15 ms, the switch is opened again to simulate the removal of the fault.

The effects of the demagnetization on the back EMF are recorded during the whole switching operation. The short circuit current and voltage for phase A are shown in figure 18 (a) and (b), respectively. The back EMF voltage using the Demag model is lower than that of the linear model after the removal of the fault because of the permanent partial demagnetization of the PM. The BH field plot of the PM is shown in figure 19 and demonstrates a partial loss in magnet's strength during short-circuit, and after the fault is removed.



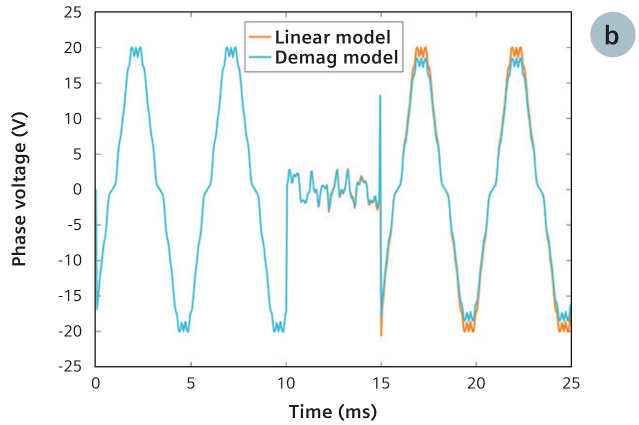


Figure 18: Test case 3 (a) Phase current during short circuit (b) EMF – Phase voltage using the Demag and linear models.

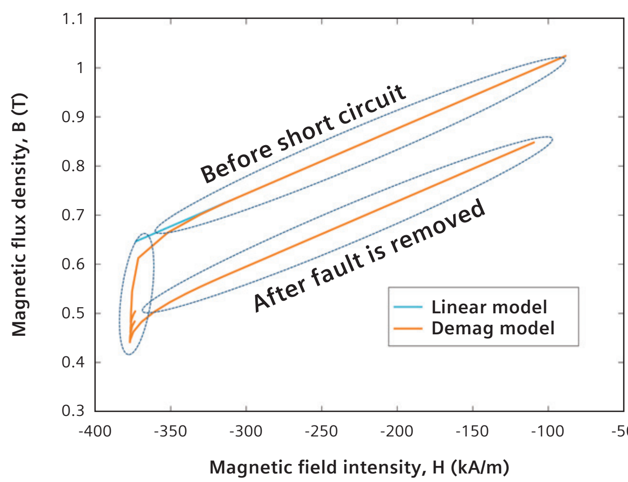


Figure 19: Test case 3 – BH plot for N42 permanent magnet during short circuit fault in the magnetization direction.

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