DIGITAL INDUSTRIES SOFTWARE

Advanced material modeling in Simcenter 3D

Executive summary

In recent years, computer-aided design (CAD) tools have become the first choice for machine designers to predict the performance of the proposed electrical machine. Efficient design requires the use of computer simulation and an understanding of the underlying physics and material properties. Modern electrical machines are subjected to strict environmental and efficiency regulations. The design's accuracy would be questionable if it were analyzed using the material models developed during the last century. These models rely on ideal operating conditions, such as sinusoidal excitation sources, fixed temperature, etc. This white paper explores advanced material modeling capabilities in Simcenter™ 3D software, including hysteresis modeling, accurate iron loss predictions, incorporating iron losses in the field solutions and irreversible demagnetization modeling of permanent magnets. These advanced features may be helpful to engineers and scientists developing next-generation electrical machines.

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Introduction

Modern society relies on electromechanical systems to generate electrical energy from mechanical energy. This is used for many essential applications, such as automating mechanical processes and replacing the power units in transportation systems. Electric machine designers are pushing the limits of conventional design and simulation techniques to meet the stricter environmental regulations for efficiency and noise. Materials lie at the heart of the electric machine design. Increasing the efficiency of an electromechanical system is highly dependent on better use of magnetic materials and a reduction of the losses incurred in them. In recent years, CAD tools have become machine designers' first choice for predicting the performance of a proposed machine. Efficient design requires the use of computer simulation, which depends on an understanding of the underlying physics and the material properties. This article explores the material modeling capabilities that Simcenter 3D offers machine designers for accurate machine design and analysis. Simcenter 3D is part of the Xcelerator portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software.

Electrical steels

Hysteresis modeling

Most commercial finite element (FE) based CAD tools use the single-valued B-H curves to represent the magnetic relationship of electrical steels. In the postprocessing stage, the iron loss is calculated using the Steinmetz equation-based empirical formulae. The single-valued B-H curves are extracted from the manufacturer's provided material data. Their mathematical representation in FE solvers is computationally fast and cheap and exhibits robust convergence. Still, they do not represent the physical behavior of the ferromagnetic material inside an electromagnetic device. Such models can lead to different field solutions, affecting global quantities such as the supply current, especially in devices with no air gaps.[1]

Hysteresis modeling is essential for accurately representing the physics of magnetic materials. The Jiles-Atherton (JA) model is one of the most popular physics-based hysteresis models.[2] It explains the hysteresis loss mechanism with the theory of domain wall motion. The two modes of domain wall transitions (bending and translational movements) in a magnetic material result in reversible and irreversible magnetization. The total magnetization in a material is computed using the following equation.

Equation 1

$$\frac{dM}{dH} = \frac{(1-c)\frac{dM_{irr}(c,k)}{dH_{eff}} + c\left(\frac{dM_{an}(M_s,a,\alpha)}{dH_{eff}}\right)}{1-\alpha\,(1-c)\frac{dM_{irr}(c,k)}{dH_{eff}} - \alpha\left(\frac{dM_{an}(M_s,a,\alpha)}{dH_{eff}}\right)}.$$

Where M_{an} (M_s, a,α) is the anhysteretic magnetization, M_s is the saturation magnetization, α is the inter-domain coupling coefficient, a is a parameter that determines the shape of the anhysteretic curve, k is the pinning coefficient and c is the domain wall flexibility coefficient.

Simcenter 3D software features the vector Jiles-Atherton model for incorporating hysteresis loss in the field solutions.[3] The details of the model and its significance in solving real-world machines are discussed here.[4]

Identification methods

When using Simcenter 3D, it is recommended to use the Jiles-Atherton model for non-oriented steels only, which typically have coercivities under 200 amperes per meter (A/m). Allowing broader ranges of the Jiles parameters would significantly increase the computational time for identifying the parameters and encourage users to use the Jiles-Atherton model for permanent magnets (PMs), which will not work well. Therefore, the ranges for the Jiles parameters are limited to model the B-H loops experienced by most non-oriented steels (table 1).

Table 1. Jiles-Atherton parameters and their ranges.

Parameters	M_s	α	a	c	k
Units	A/m		A/m		A/m
Range	$(0.5 – 2) \times 10^6$	$10^{-9} – 10^{-2}$	5 – 2000	0.02 – 1	10 – 2000

Simcenter 3D software provides three methods to specify parameters for the Jiles-Atherton model. The users can choose the appropriate method in the material editor to calculate the parameters. However, these parameters are only used in the transient 2D solver. Hysteresis model in 3D uses a different set of parameters. Therefore, the transient 3D solver computes the model parameters on the fly and chooses the appropriate method based on the available data.[5]

a. Method 1: Enter Jiles-Atherton parameters.
   This method is mainly suited for researchers and expert users who want to use their Jiles-Atherton parameters from published research papers or other sources. The material editor verifies that the specified parameters result in a valid hysteresis loop. The solver ignores the single-valued B-H curve and uses the hysteresis model to represent the complete magnetic behavior of the material.

b. Method 2: Generate Jiles-Atherton parameters from permeability and iron loss data. This method uses the single-valued B-H curve and iron loss data to compute the Jiles-Atherton model. The algorithm tries to match the tips (provided by the single-valued B-H curve) and areas (provided by the iron loss data) of the B-H loops at different induction levels. It returns one of many solutions that equally respect the permeability and iron loss data. Those solutions would be adequate in sinusoidal problems where average losses are of interest. However, there could be other B-H loops satisfying these criteria. Therefore, the availability of additional information, such as coercivity and remanence, improves the accuracy of the predictions. For example, four B-H loops computed using the coefficients calculated from the permeability and iron loss data are compared against the measured B-H loop for 35WW300 NO electrical steel in figure 1. The default parameters available in the material library were derived using a technique that requires more data and more computing time. However, they were computed using the permeability and iron loss data only; coercivity and remanence information was not available. The parameters for a small subset of Simcenter 3D library materials are provided in the material database section.

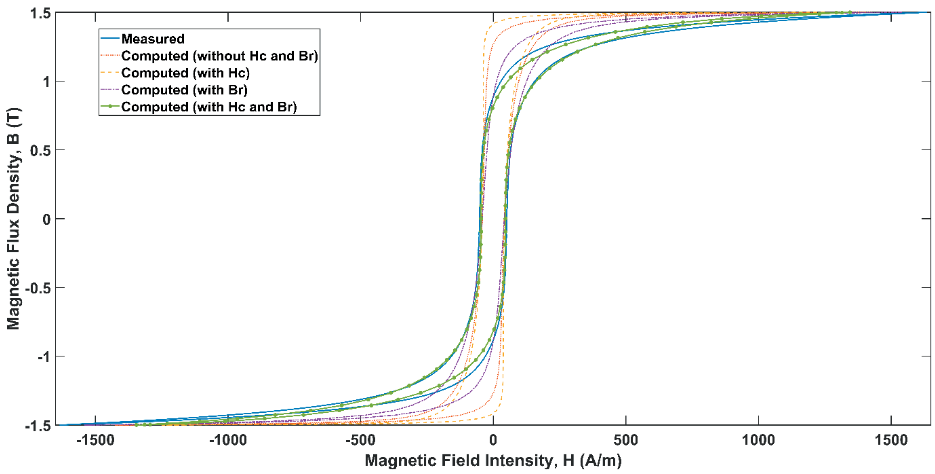


Figure 1. Measured and computed hysteresis loops using method 2 for 35WW300 non-oriented electrical steel at B equals 1.5 Tesla (T).

Table 2. The computed Jiles-Atherton parameters using method 2 for 35WW300 NO electrical steel.

	M_s	α	a	c	k
Computed (with Br)	1217466.6250	6.0419e-05	32.4402	0.2633	69.3180
Computed (with Hc)	1197253.3915	4.2619e-05	5.0003	0.0741	63.9081
Computed (without Hc and Br)	1202413.4278	4.3558e-05	12.0228	0.1365	64.1063
Computed (with Hc and Br)	1320008.1930	4.0459e-04	171.1129	0.6315	137.9166

c. Method 3: Generate Jiles-Atherton parameters from the increasing or decreasing branch of the saturated B-H loop.
This method is suited for users that have access to the material measurements and can provide the decreasing and increasing branch of the saturated B-H loop. The software is used to compute the parameters and display the computed B-H loop on the user-specified data, as shown below.

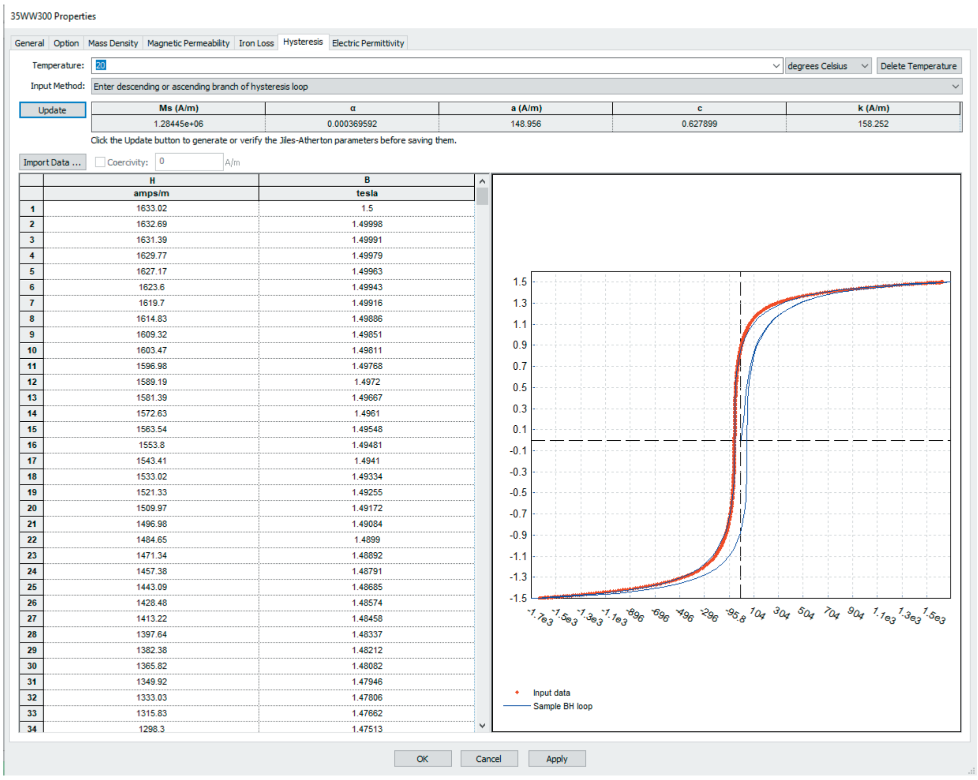


Figure 2. Measured and computed hysteresis loops using method 3 for 35WW300 non-oriented electrical steel at B equals 1.5 T.

Material database

There are 130 suitable soft magnetic materials in the Simcenter 3D material database. The Jiles-Atherton parameters were carefully computed from the available single-valued B-H curve and iron loss data (method 2). The Jiles-Atherton parameters for a subset of library materials are provided in table 3.

Table 3. Materials with the Jiles-Atherton parameters in the database.

Material	M_s	α	a	c	k
Losil 340/50	1320000	0.000470	195	0.619	196
Newcor 1000/65	1333734	7.078e-07	24.6	0.020	209
Hiperco 50A 0.006	1640000	0.000028	10	0.0704	52.2
M-15 26 Ga	1380000	0.000553	243	0.652	191
M-19 26 Ga	1400000	0.000647	292	0.696	220
M-27 26 Ga	1450000	0.000709	330	0.67	241
M-36 26 Ga	1470000	0.000731	346	0.689	268
M-43 26 Ga	1460000	0.000668	314	0.75	259
M-47 26 Ga	1470000	0.000727	344	0.73	274
36F145	1330000	0.000571	244	0.698	186
64F190	1400000	0.000737	331	0.672	253
M1000-65A	1310000	0.000184	35.8	0.0716	235
M235-35A	1330000	0.000664	288	0.741	198
M1000-65D	1320000	0.000145	23.7	0.080	212
35PN210	1350000	0.000690	305	0.796	207
Arnon 7	1340000	0.000614	266	0.614	173
NO20	1380000	0.000719	322	0.719	221
Vacodur 50 Mechanical	1670000	0.0000001	16.8	0.064	110
Vacoflux 50	1764117	0.000062	21.8	0.072	42.8
23PM85	1330000	0.000732	313	0.704	235
M22: USS Dynamo -- 26 Gage	1350000	0.000580	248	0.509	193
M4: Unisil/alphasil 28 M4	1610000	0.000267	137	0.711	129

Application example

The simulation model of the voltage-driven unskewed induction motor is shown in figure 3. The quarter model was solved for 25 supply cycles — frequency equals 50 hertz (Hz). This uses the 2D transient solver with motion for simulation purposes. Shaded plots for computed B fields at t equals 500 milliseconds (ms) are also shown for both the single-valued and hysteresis models. The difference in rotor position at 500 ms for both models can be noticed. The torque characteristic of the induction machine is shown in figure 3 (d). The hysteresis model predicts higher overshoots in the torque waveform. Still, the transients die out faster than the single-valued model because of the energy dissipation in the ferromagnetic material changing the time constant of the system. This also implies that a steady-state is achieved earlier and hysteresis simulations can be run for a lower number of time steps. There is no significant difference in values at the steady-state. More details can be found here.[4]

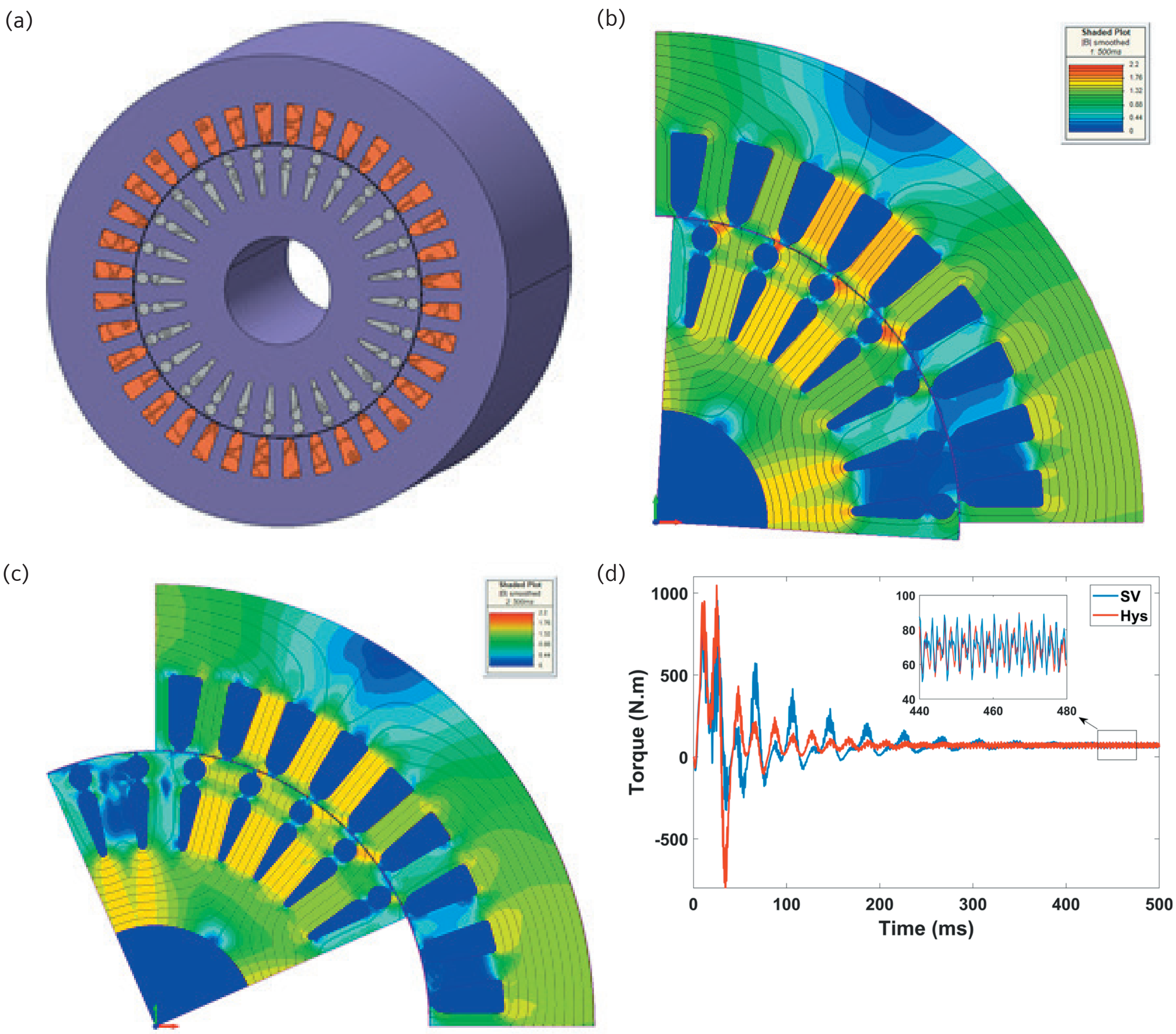


Figure 3. Simulation model of an induction motor (a). B field shaded plot at t equals 500 ms computed using the single-valued (b) and hysteresis models (c). Torque calculated using the single-valued and the hysteresis models (d).

Iron loss calculation

Simcenter 3D software uses the Steinmetz equation to calculate the iron loss in postprocessing for static and transient solvers. The loss calculation in time-harmonic solvers is discussed in the iron loss calculation method for complex permeability section.

Equation 2

$$P = K_h f^{\alpha} B^{\beta} + K_e f^2 B^2$$

K_h and K_e are the hysteresis and eddy current loss coefficients. The first term in equation 2 represents hysteresis and anomalous loss, while the second term only represents the eddy current loss.

Equation 2 was initially proposed to calculate the iron loss in laminated materials only. However, in Simcenter 3D, the equation is used to calculate iron loss for other materials — for example, powdered core materials.[6]

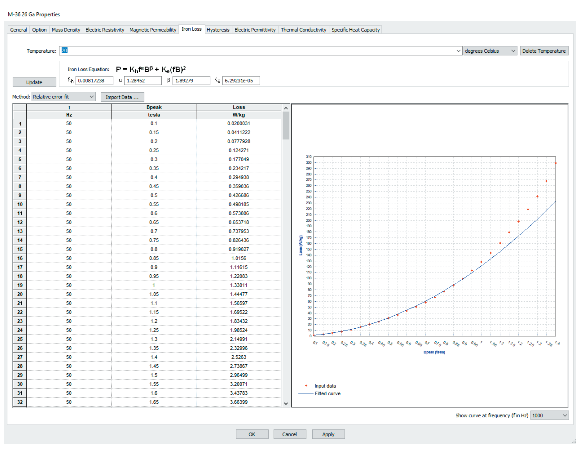
Steinmetz coefficients identification methods

Simcenter 3D provides three methods to define the Steinmetz coefficients:

1. Direct entry — The user has to specify the coefficients directly.
2. Absolute error fit — The algorithm identifies Steinmetz coefficients by minimizing the absolute error between the user-specified iron loss data and computed data. As a result, iron loss values at higher induction levels and frequencies are weighted more when using this method.
3. Relative error fit — The algorithm identifies Steinmetz coefficients by minimizing the relative error between the computed loss and user-specified iron loss data. It distributes the relative error uniformly over the range of induction levels across different frequencies, which provides high accuracy at low induction levels and frequencies.

In figure 4, the absolute error fit method performs better than the relative error fit method in estimating losses at higher induction levels and frequencies.

(a)



(b)

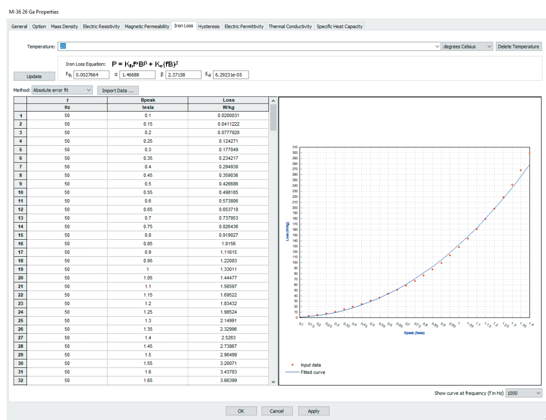


Figure 4. Steinmetz coefficients identification using relative error fit method (a) and absolute error fit methods (b) for M36-26Ga NO electrical steel.

Computation of K_e

Simcenter 3D software computes K_e analytically from the lamination thickness (d), the electric resistivity (ρ)/conductivity (σ) and the mass density using equation 3. Steinmetz fitting methods do not compute K_e if it has already been calculated analytically.

Equation 3

$$K_e = \frac{\sigma \pi^2 d^2}{6\rho}$$

Simcenter 3D software follows specific rules to calculate Steinmetz coefficients for a material (table 4).

Table 4. Materials with the Steinmetz coefficients in the database.

Lamination Thickness	Conductivity/ Resistivity	K_e	
✓	✓	Computed using (3)	Lamination eddy current loss is removed from the total power loss and the hysteresis loss coefficients are calculated using the modified loss.
✓			All four coefficients are calculated.
	✓	0.0	The hysteresis loss coefficients are calculated.
		0.0	The material is a solid insulator. Three hysteresis loss coefficients are calculated.

Material database

There are 144 magnetic materials in the material library with iron loss data. Below are the iron loss coefficients computed for a subset of Simcenter 3D library material using either the absolute or relative error fit methods. Please note that if the iron loss data is specified at one frequency only, α is set to 1.

Table 5. Materials with the Steinmetz coefficients in the database.

Material	K_h	α	β	K_e
Losil 340/50	0.01806915	1	2.39487873	0.000127991
Newcor 1000/65	0.02977212	1	2.13403687	0.000632379
Hiperco 50A 0.006	0.00886648	1.11736055	1.59679506	1.17626E-05
M-15 26 Ga	0.01870407	1	2.04860956	8.63615E-05
M-19 26 Ga	0.01104342	1.10686867	2.39234406	9.13439E-05
M-27 26 Ga	0.02250816	1	1.90710988	9.49976E-05
M-36 26 Ga	0.0027664	1.46687853	2.3715803	6.29231E-05
M-43 26 Ga	0.00121545	1.61512376	2.59517732	4.01754E-05
M-47 26 Ga	0.00630255	1.12240926	3.65152416	0.000130239
36F145	0.01355511	1.06614274	2.12737374	5.10008E-05
64F190	0.01894579	1	2.0129917	0.000161188
M1000-65A	0.04905064	1	1.77344896	0.000495003
M235-35A	0.00893187	1.1565734	2.15599487	4.49385E-05
M1000-65D	0.02977212	1	2.13403687	0.000632379
35PN210	0.00807037	1.16330972	1.94855688	4.49385E-05
Arnon 7	0.01750447	1.11439897	11.61551053	1.30722E-05
NO20	0.0100626	1.17057757	1.94685587	1.65403E-05
Vacodur 50 Mechanical	0.01874177	1.0660086	2.33464247	5.90853E-05
Vacoflux 50	0.01055222	1.05763952	1.4776452	5.68427E-06
23PM85	0.02336332	1	2.04680945	5.39432E-05
M22: USS Dynamo -- 26 Gage	0.03427562	1	1.76358468	9.56226E-05
M4: Unisil/alphasil 28 M4	0.00527393	1	2.73604453	5.48759E-05

Complex permeability

Simcenter 3D software incorporates iron losses in the field solutions in the time-harmonic solver using the complex permeability. The imaginary part of the complex permeability represents a loss in magnetic materials. The concept is similar to the dielectric loss tangent, represented by the ratio of the complex and real parts of the permittivity, ϵ.

Equation 4

$$tan^{e}\,\delta = \frac{\epsilon''}{\epsilon'}$$

The magnetic loss tangent is given in equation 4.

Equation 5

$$tan^{m}\,\delta = \frac{\mu''}{\mu'}$$

Further, $tan^{e}\delta$ and $tan^{m}\delta$ represent dielectric and magnetic loss.

Linear complex permeability

Simcenter 3D enables users to enter the real and imaginary part of the complex permeability for linear magnetic materials. The parameter solverIncludesIronLoss can also be used with SolverMaterialType to obtain the linearized complex material from the nonlinear material with iron loss data (table 4).

Nonlinear complex permeability

It is tedious for users to provide complex permeability data for nonlinear magnetic materials because the manufacturer does not offer such data in the material's datasheet. Therefore, Simcenter 3D software does not ask users to provide this data and instead computes it on the fly and uses it in the simulation. The software is used to calculate the real part of the complex permeability from the single-valued B-H curve and the imaginary part from the power loss curves, which contain the hysteresis and the eddy current losses. These computations are performed in real-time (without incurring an extra computational cost). Thus, the iron loss is incorporated in the field solutions during the simulation, which increases the accuracy of the field solutions and global quantities.

This feature is particularly useful for materials that exhibit higher iron loss or in applications that require high induction levels and high operating frequencies where the iron loss can be significantly higher.

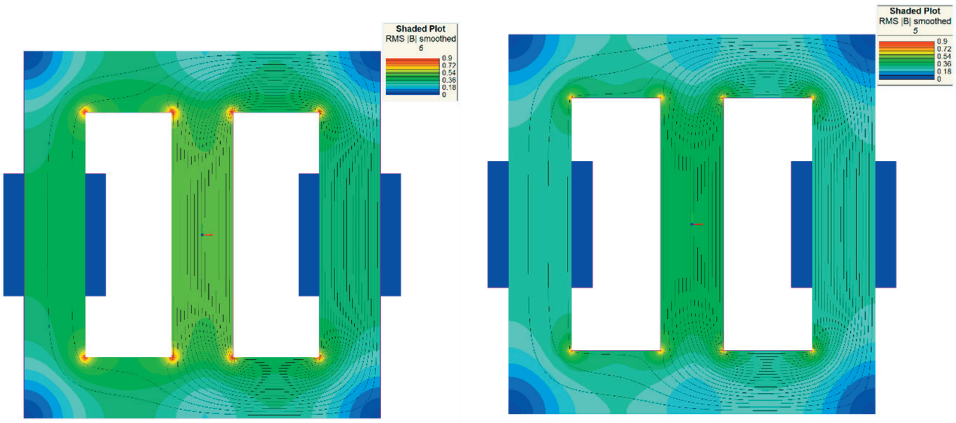


Figure 5. B field shaded plot using the real permeability (a) and the complex permeability at 1000 Hz (b).

Application example — transformer

The test bench is a three-limbed ferromagnetic core. The core is made of five M19-29 Ga, 0.48 millimeters (mm) thick steel laminations, with a conductivity of 1.78 millisiemens per meter (MS/m) and a mass density of 7650 kilograms per cubic meters (kg/m3). Two windings of 90 turns are placed on the external limbs; the resistance (at 0 Hz) of each winding is 0.32 ohms. These windings can be connected in series or supplied by two independently controlled voltage sources. Here we will only consider the case where the two windings are excited by two independent sinusoidal sources with an amplitude of 14.5 volts (V), 1000 Hz frequency and differing by 90 degrees in phase. The B field distributions using both conventional simulation (real permeability) and the complex permeability are shown in figure 5 (a) and (b). The difference is due to the increase in the iron loss that is incorporated in the field solutions.

Some of the global quantities are provided at 1000 Hz in table 6 to highlight the difference. Similar differences can arise when the material has a significant iron loss, even at low frequencies.

Table 6. Global quantities of the transformer using real and complex permeability.

Quantity	Units	Real Permeability	Complex Permeability
Stored Magnetic Energy	J	0.0105	0.00954
Coil 1: Ohmic Loss	W	0.55	0.502
Coil 2: Ohmic Loss	W	0.442	0.404
Hysteresis Loss	W	1.41	1.37
Eddy Current Loss	W	0.18	0.176

Usage

The component-level parameters, MaterialForceLinear combined with SolverIncludesIronLoss, govern nonlinear magnetic material modeling, while SolverIncludesIronLoss is used alone for linear magnetic material instances.
The material must have both permeability and iron loss curves. The user must also specify the mass density. SolverMaterialType is a top-level parameter and if set to LinearMaterialType, it overrides the MaterialForceLinear equals no at the component level. Therefore, a nonlinear material will be linearized if MaterialForceLinear equals yes or if SolverMaterialType equals LinearMaterialType.

Table 7. Material modeling with complex permeability feature in Simcenter 3D time-harmonic solvers.

<table>
<tr><th>SolverIncludesIronLoss</th><th>Linear or linearized materials</th><th>Modeling method</th><th>Material types</th></tr>
<tr><td>No</td><td>Yes</td><td>• If not linear, linearize the material
• Create a linear, isotropic and real (LIR) material
• Both hysteresis and lamination eddy current losses not part of the energy balance</td><td rowspan="4">• LIR
• NIR
• LIC
• NIC</td></tr>
<tr><td>No</td><td>No</td><td>• Use nonlinear model to represent a nonlinear magnetic material
• Create a nonlinear, isotropic and real (NIR) material
• Both hysteresis and lamination eddy current losses are not part of the energy balance</td></tr>
<tr><td>Yes</td><td>Yes</td><td>• If not linear, linearize the material to compute the real part of the complex permeability
• Use the eddy current loss coefficient, Ke, to calculate the imaginary part of the complex permeability
• Create a linear, isotropic and complex (LIC) material
• Only lamination eddy current loss is part of the energy balance
• Hysteresis loss is calculated in the postprocessing</td></tr>
<tr><td>Yes</td><td>No</td><td>• Use nonlinear B-H and iron loss curves in the solver to compute complex permeability.
• Model as an nonlinear, isotropic and complex (NIC) material in the solver
• Both hysteresis and lamination eddy current losses are part of the energy balance</td></tr>
</table>

If iron loss data is not provided, the SolverIncludesIronLoss parameter is irrelevant.

Iron loss calculation method

Simcenter 3D software calculates the time-averaged power loss in a magnetic material using the following equation.

Equation 6

$$P_{avg} = \frac{1}{2}\omega v_{imag} B^2.$$

Where ω is the angular frequency, v_{imag} is the imaginary component of the reluctivity and B is magnetic flux density. Equation 6 calculates hysteresis and eddy current losses independently using v_{imag} that is obtained from the hysteresis or the eddy current loss computed using Equation 2 in the preprocessing.

This method is more accurate, faster and replaces the legacy iron loss calculation method for materials with isotropic permeability and iron loss in time-harmonic solvers.

Permanent magnets

Simcenter 3D software offers a rich collection of linear and nonlinear permanent magnet (PM) materials with temperature-dependent magnetic properties in its database. The software differentiates nonlinear materials into two categories, Strong and Weak. Temperature-dependent nonlinear B-H curves are shown in figure 6 for a nonlinear Strong PM material.

Modeling

Commercial FE solvers treat most PMs as linear materials for various reasons, including the ease of numerical implementation and the lack of measured data. Simcenter 3D software can be used to represent both linear and nonlinear PMs. It employs different modeling methods in the solver based on PM type.

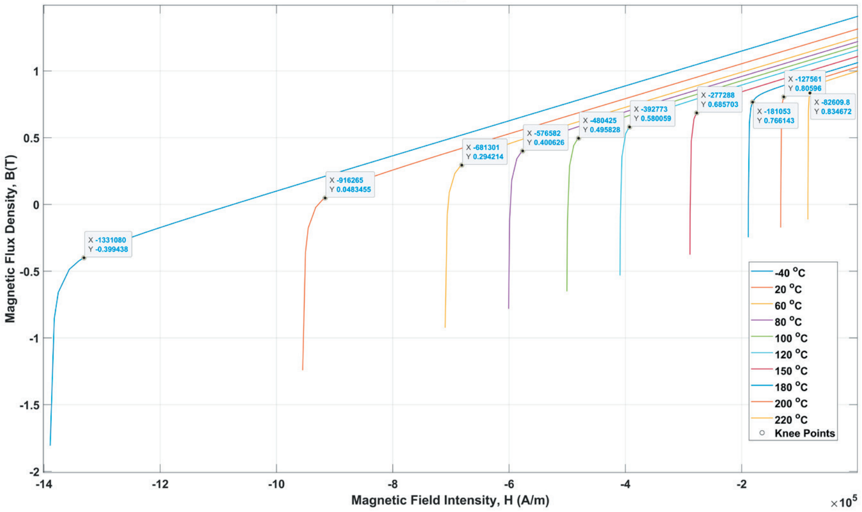


Figure 6. Temperature-dependent B-H properties and the corresponding knee points of a strong PM.

The component-level parameter, MaterialForceLinear, when combined with the Permanent magnet type — Strong/Weak setting, governs the nonlinear permanent magnet modeling in Simcenter 3D.

Table 8. PM modeling in Simcenter 3D.

Permanent magnet type	MaterialForceLinear	Modeling method	Material types
Weak	**Yes**	• Linearizes the nonlinear B-H curve by computing the linear permeability at H equals 0 • Models an LIR material with the same permeability in all directions	• LIR
Weak	**No**	• Simulates reversible demagnetization • Uses nonlinear B-H curve data in the second quadrant (including points at B equals 0 and H equals 0) to model the nonlinear permanent magnet • Points on the B-H curve with negative B values are ignored • Models an NIR material with the same permeability in all directions	• NIR
Strong	**Yes**	• Linearizes the nonlinear B-H curve using a portion of the curve above the knee point to compute the linear permeability • Models a linear, anisotropic and real (LAR) Material with permeabilities in cross magnetization directions set to μ_o	• LAR
Strong	**No**	• Simulates irreversible demagnetization • Uses the whole nonlinear B-H curve to model the nonlinear permanent magnet and computes recoil curves • Models a nonlinear, anisotropic and real (NAR) material with permeabilities in cross magnetization directions set to μ_o	• NAR

Reversible demagnetization model

Weak PMs, such as Alnico magnets exhibit a smoothly varying behavior in the second quadrant. Simcenter 3D software treats them as nonlinear electrical steels and is used to model the whole B-H curve. Nevertheless, the magnetization in all cases is reversible. For example, the magnet will regain its strength once it goes past the knee point and returns.

Irreversible demagnetization model

The irreversible demagnetization model in Simcenter 3D software is a dynamic model with history. It tracks the movement of the operating point in real time and maintains the history of knee point. and is important in the fault analysis of an electric machine. It can be used to predict the B-H behavior of PM in the second quadrant with reasonable accuracy and does not require additional material information or incur additional computation costs.

The B-H curves of PMs such as NdFeB exhibit two almost linear sections joined by a sharp curve known as a knee point in the second quadrant of the B-H plane.[7] Once the operating point moves past the knee point, the magnet is no longer considered good because it has lost its magnetization. There is no point in using a faulty material in designing an electrical machine if this behavior is not desired. In this method, the demagnetization curve of the PM is divided into two parts — before and after the knee point. First, the knee point is identified according to the method given in the Magnetic Materials Producers Association (MMPA) standard 0100-00.[8] The slope of the first segment μ_{R1} (before knee point) is then identified by linearly fitting the first segment between $0.2H_c$ to $0.7H_c$. The slope of the second segment μ_{R2} (after the knee point) is the slope of the straight line joining the knee point and the H_c. Once the applied field is lower than the knee fields (for example, crosses the knee point), the change in magnetization is irreversible and the slope of the B-H line changes. If a reversal of input is encountered, the new path to follow is the line with slope μ_{R1} starting from the updated knee point. A reasonable assumption is that the slope of the recoil curves is the same as μ_{R1}. If nonlinear B-H data is not available, the user can still model irreversible demagnetization by providing three data points — remanence, knee point and coercivity. The algorithm will approximate the nonlinear curve using the provided information and the irreversible demagnetization model will use it in the solver.

The application of the irreversible demagnetization model on a three-phase interior PM motor used for automotive applications is shown in figure 7. The motor is subjected to current loading at 120 degrees Celsius (C). The variation of the three-phase supply current can be divided into five stages, as shown in figure 7 (b). 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 irreversible demagnetization model is presented in figure 7 (c). The torque at low current (90 A) is the same for both models. However, as the current increases, the PM goes into partial demagnetization and torque is computed using the irreversible demagnetization model during stages three to five is less than that from the linear model due to a loss in PM's strength. More details of the problem with different cases can be found here.[9]

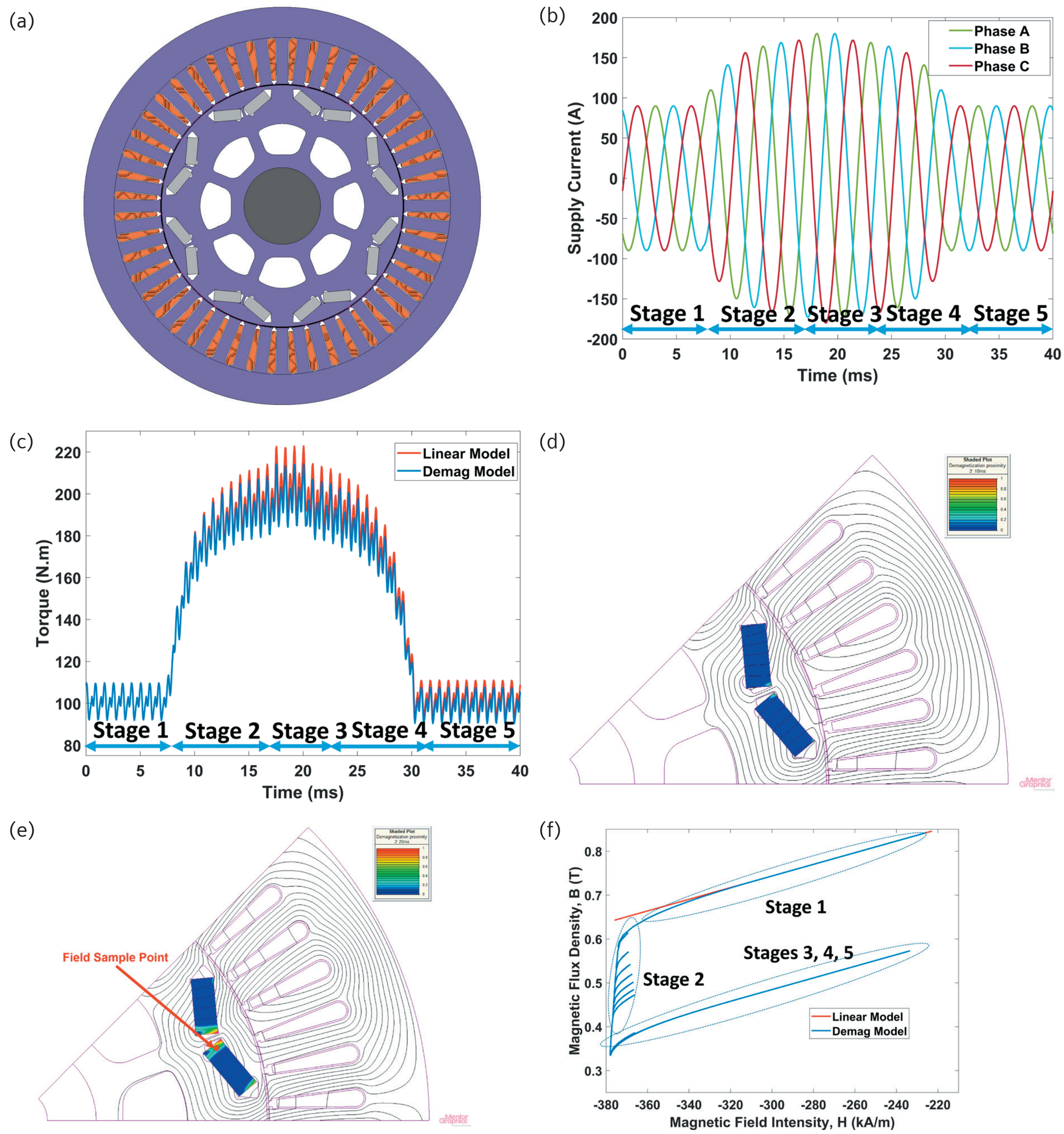


Figure 7. Simulation model of the IPM motor (a), supply current (b), and torque using the linear and the irreversible demagnetization models (c). Demagnetization proximity plots for the linear model at 10 ms (d), the irreversible demagnetization model at 20 ms (e) and B-H plot for at the sample field point in the magnetization direction (f).

Material database

The list of PM libraries available to Simcenter 3D users for their designs:

1. Alnico Permanent Magnet Materials – nonlinear, Weak
2. Arnold Magnetic Technologies Ferrite Materials – nonlinear, Strong
3. Arnold Magnetic Technologies NdFeB Materials – nonlinear, Strong
4. Arnold Magnetic Technologies Samarium Cobalt Materials – nonlinear, Strong
5. Ceramic Permanent Magnet Materials – linear, except:
    - Ceramic ferrite – nonlinear, Strong
6. Magnequench NdFeB Materials – linear
7. Neodymium Permanent Magnet Materials – linear
8. Samarium Cobalt Permanent Magnet Materials – linear
9. Vacuumschmelze Magnet Materials – linear, except:
    - Vacomax 145S – nonlinear, Strong
    - Vacomax 170 – nonlinear, Strong
    - Vacomax 200 – nonlinear, Strong
    - Vacomax 225 – nonlinear, Strong
    - Vacomax 225HR – nonlinear, Strong
    - Vacomax 240 – nonlinear, Strong
    - Vacomax 240HR – nonlinear, Strong

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