LBNL Eng. Note: SU-1010-4842

Check of IFCC Equivalent Magnetization Implementation in ANSYS User Elements using a Single Strand Model

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Within ANSYS there is the capability for users to create their own element type by writing the code which defines the element's properties and the generation of its finite element matrices. After the compilation of a custom ANSYS executable, all other aspects of the software (such as geometry generation, meshing, solving, and post-processing) are compatible with the user element. Control over the generation of the matrices allows for customization of the mathematical formulation, material properties, and many other aspects of the element. An important new behavior added for the simulation of superconducting magnets is interfilament coupling currents (IFCC). The FEM implementation of IFCC using an equivalent magnetization approach is first described. Following this, user defined elements developed at Berkeley [1] are shown reproducing expected results for a single strand in a changing external background field.

Contents

1 Equivalent Magnetization for IFCC

Interfilament coupling currents (IFCC) are an important loss mechanism for superconducting magnets. Their relatively short time constant (tens of milliseconds or less) and localized heat deposition within the strand make them an effective mechanism for magnet quench back. As shown in Fig. 1, these induced currents flow along the superconducting filaments which are twisted along the length of the strand and then across the strand matrix.

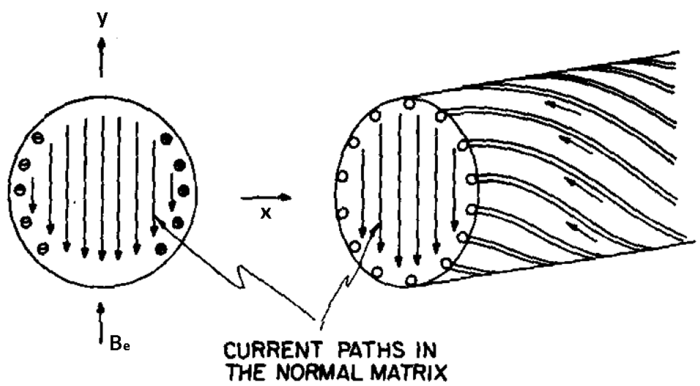


Figure 1: The path of interfilament coupling currents induced by a changing vertical field is shown (Fig. from [2]). The current flows along the twisted filaments and then across the strand matrix. This results in strand magnetization as well as resistive losses in the matrix material.

For a uniform field change within the strand, the induced axial current is typically approximated using a cosine theta (dipole producing) current density [2, 3]

$$g_z(\theta) = \dot{B}_i \left(\frac{L}{2\pi}\right)^2 \frac{cos(\theta)}{\rho_{et}}, \tag{1}$$

where $\dot{B}_i$ is the vertical field change within the strand, L is the filament twist pitch, and ρ_{et} is the effective resistivity of the strand matrix (which includes contact resistance between the matrix and the filaments). If B_e is an applied, uniform external vertical field, the field within the strand is depressed by the induced IFCC currents as

$$B_i = B_e - \frac{1}{2}\mu_0 g_z(\theta = 0) \tag{2}$$

$$B_i = B_e - \tau \dot{B}_i, \tag{3}$$

where the natural time constant for the induced current is clearly

$$\tau = \frac{\mu_0}{2\rho_{et}} \left(\frac{L}{2\pi}\right)^2. \tag{4}$$

The strand magnetization is then given by

$$M_e = -\frac{4}{\mu_0 \pi} \int_0^{\pi/2} g_z(\theta) cos(\theta) d\theta \tag{5}$$

$$M_e = -\frac{2\tau}{\mu_0} \dot{B}_i. \tag{6}$$

For those reviewing this approach in Wilson's textbook [3], it is helpful to note there is a missing μ_0 in Equation 8.51 (to match Eqn. 6). The element documentation for USER102 [4] shows how this equivalent magnetization approach to modeling IFCC can be added to the vector potential formulation, leading to the addition of a curl-curl term in the damping matrix of the FEM. The induced currents deposit energy with a power per unit volume of

$$P_e = \vec{M}_e \cdot \dot{\vec{B}}_i, \tag{7}$$

which in many causes leads to IFCC being an important quench back mechanism.

2 Single Strand IFCC Predictions

To produce the equations for comparison with the FEM model, a single strand is assumed to be located in a background field B_e. This background field is ramped linearly from zero with a constant rate $\dot{B}_e \equiv dBdt$. In this case the equation for the uniform field within the strand can be written as (see Eqn. 3)

$$B_i = dBdt\, t - \tau \dot{B}_i, \tag{8}$$

which leads to the field within the strand as a function of time being

$$B_i(t) = dBdt\left[t + \tau\left(e^{-t/\tau} - 1\right)\right]. \tag{9}$$

The magnetization and field intensity are then

$$M_e(t) = \frac{-2\tau}{\mu_0} dBdt\left(1 - e^{-t/\tau}\right), \tag{10}$$

and

$$H_i(t) = \frac{dBdt}{\mu_0}\left[t + \tau\left(1 - e^{-t/\tau}\right)\right]. \tag{11}$$

The heat generation per unit volume (see Eqn. 7) is given by

$$P_e(t) = \frac{2\tau}{\mu_0}\dot{B}_i^{\,2} = \frac{2\tau}{\mu_0} dBdt^2\left(1 - e^{-t/\tau}\right)^2. \tag{12}$$

3 The Single Strand Model

A single strand model was used to verify the expected output as given in Section 2. This model consists of two regions including a single strand and a surrounding air box for magnetic boundary conditions (see Fig. 3). The same mesh density was used for all simulations and is illustrated in the figure. PLANE53 elements were used for the air region, and the user defined element USER102 for the strand. Boundary conditions as a function of time were applied to the vector potential DOF on the outer edges of the air box to create a uniform applied background field with a constant rate of change (starting from zero).

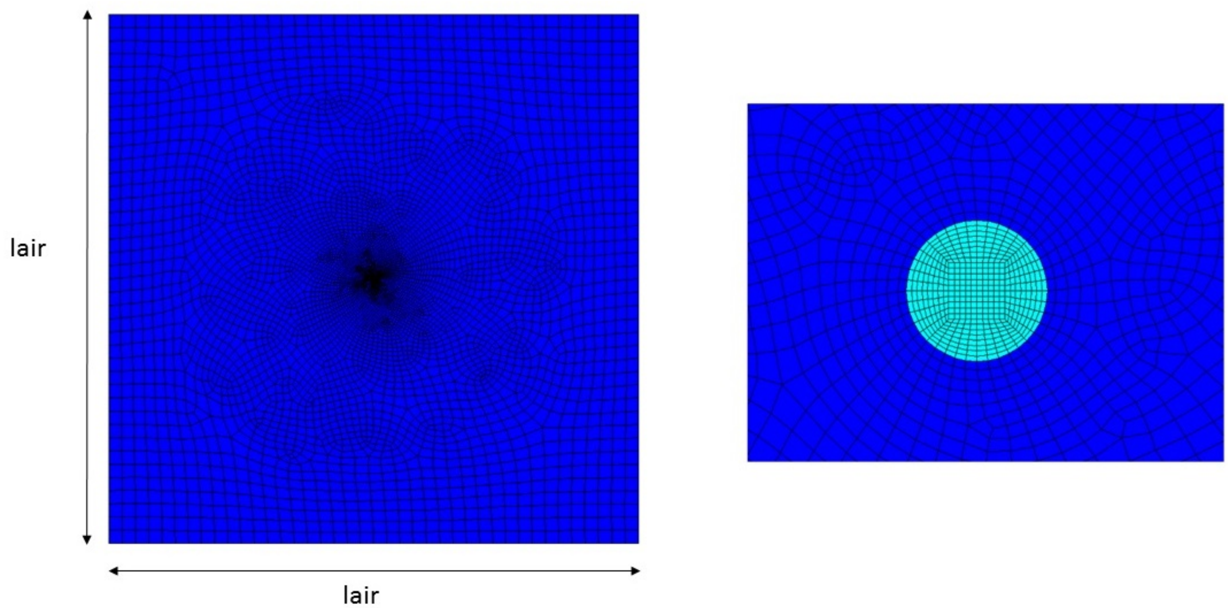
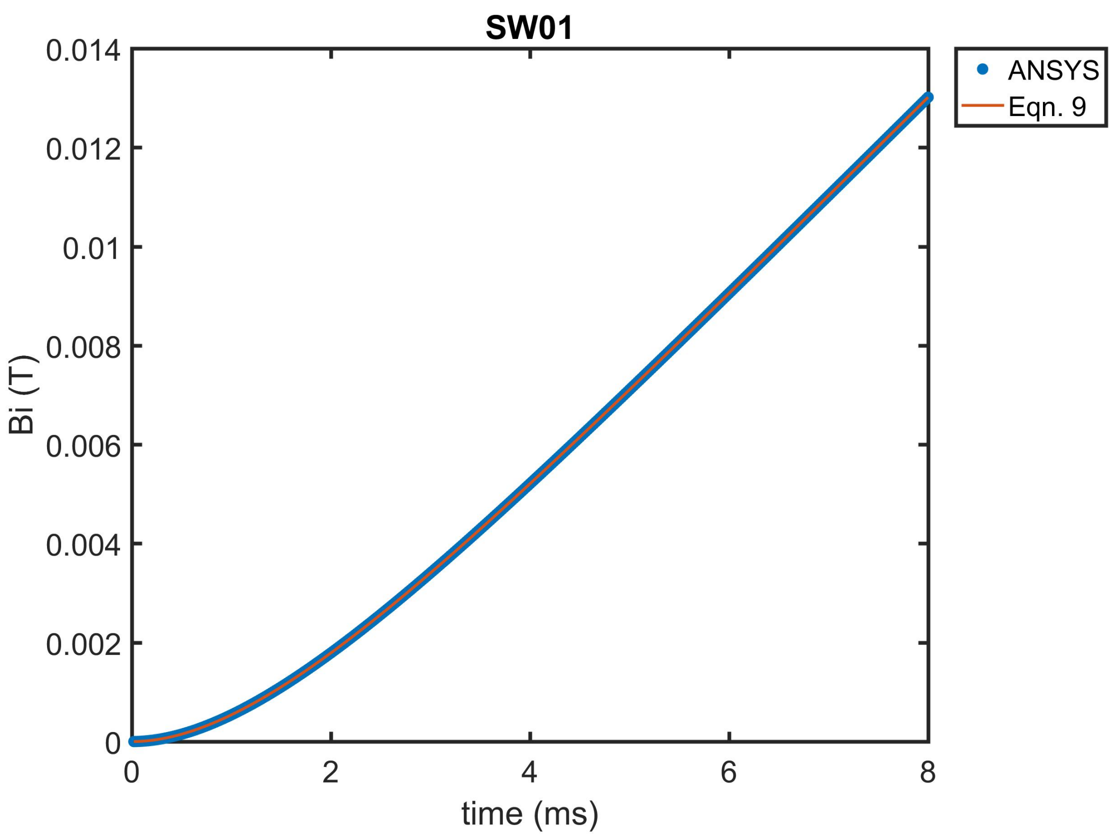


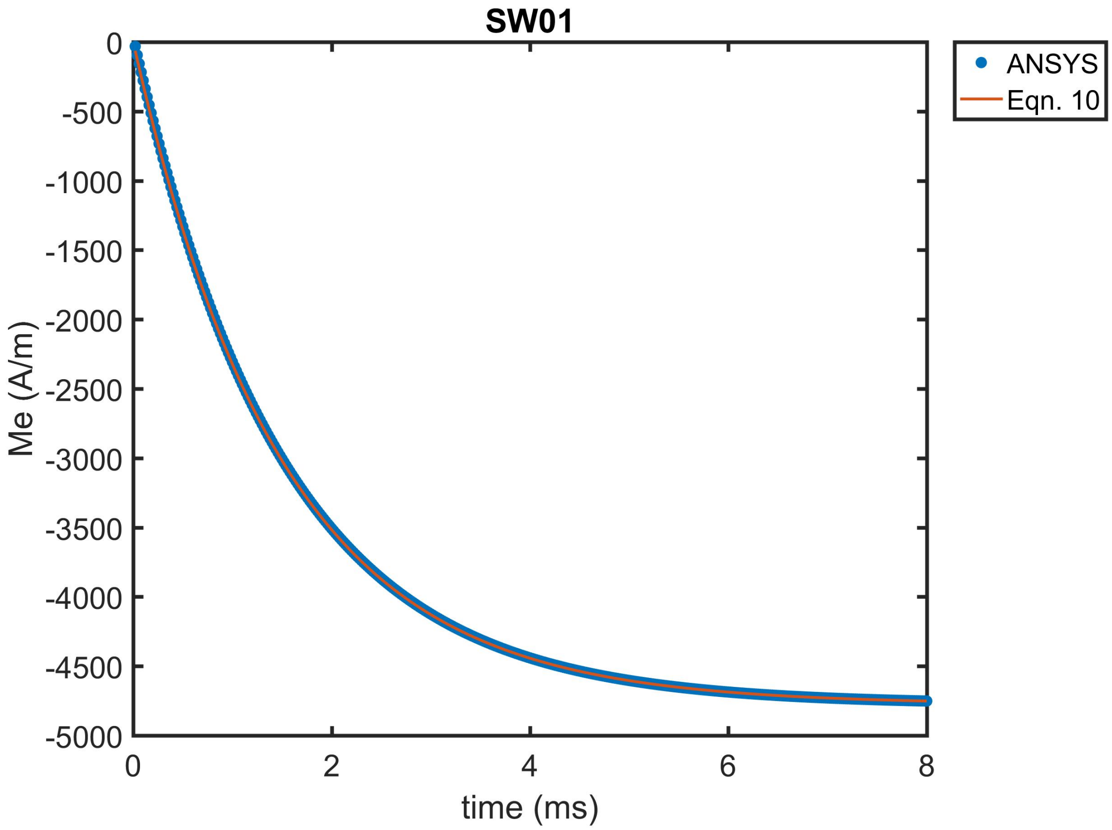
Figure 2: The ANSYS model consists of a single strand surrounded by an air region for magnetic boundary conditions.

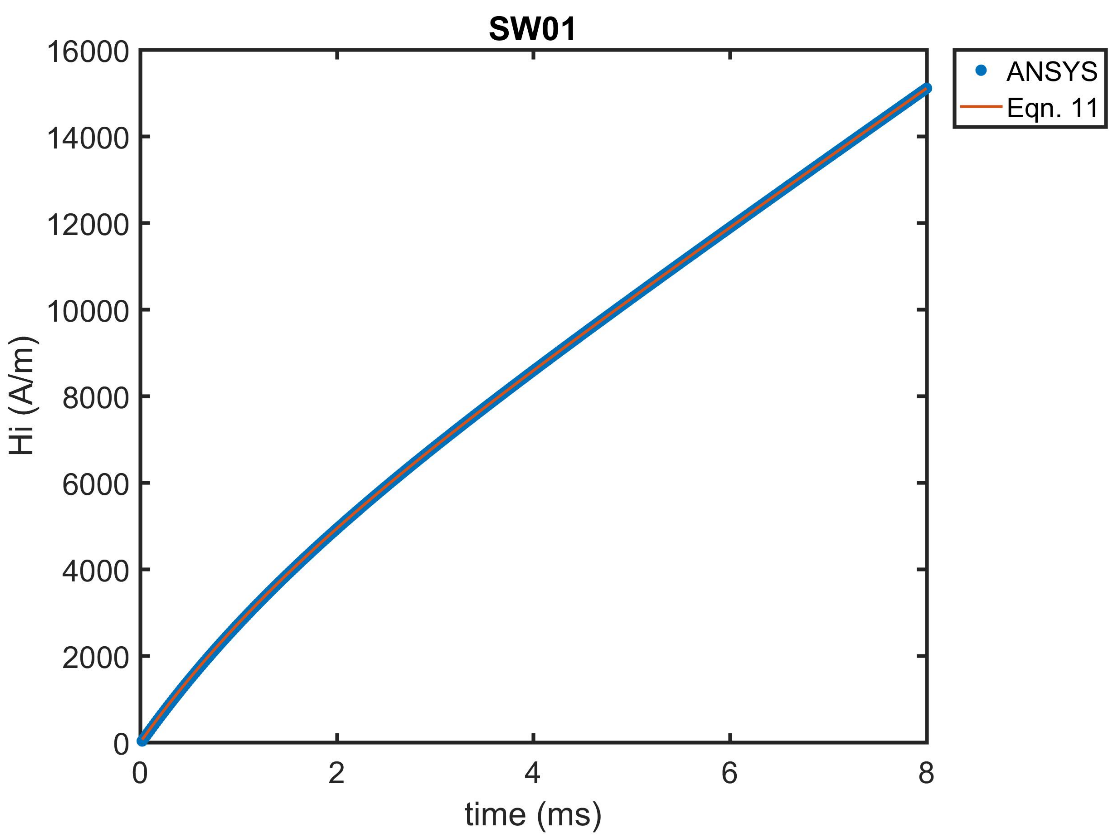
4 Test SW01: Induced Magnetization and IFCC Losses

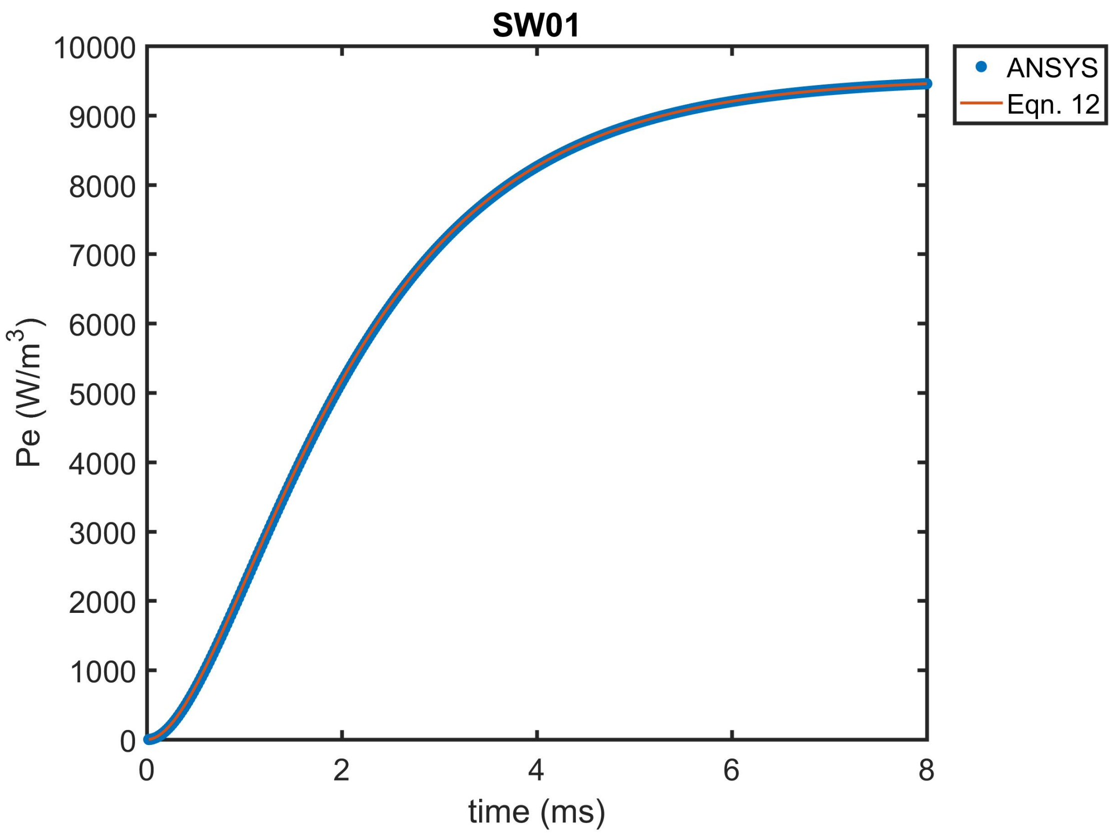
This test verifies the expected behavior given in Section 2 for an external vertical magnetic field changing over the strand at a constant rate. In this case a fixed IFCC time constant τ is assumed.

Active physics	EM
IFCC	YES
Quench state	Always SC
Boundary (lair)	100 mm
Strand diameter	0.8 mm
Constant τ	1.5 ms
External loads	Field Ramp, t=(0,8) [ms], Δt=0.02 [ms], dBdt = 2.0 [T/s]
Output	Average strand magnetic field B_i, see Equation 9
	Average strand magnetization M_e, see Equation 10
	Average strand field intensity H_i, see Equation 11
	Average strand power P_e, see Equation 12




SW01
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
Me (A/m)
0
2
4
6
8
time (ms)
ANSYS
Eqn. 10


SW01
16000
14000
12000
10000
8000
6000
4000
2000
0
Hi (A/m)
0
2
4
6
8
time (ms)
ANSYS
Eqn. 11


SW01
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Pe (W/m3)
0
2
4
6
8
time (ms)
ANSYS
Eqn. 12

References

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[2] G. Morgan, "Theoretical Behavior of Twisted Multicore Superconducting Wire in a Time-Varying Uniform Magnetic Field," *Journal of Applied Physics*, vol. 41, p. 3673, 1970.

[3] M. Wilson, *Superconducting Magnets*. Oxford University Press, 1983.

[4] L. Brouwer, "Documentation for USER102: a 2D User-Defined Electromagnetic Element in ANSYS," *LBNL Eng. Note: SU-1010-4838, R1.0*, 2019. [Online]. Available: https://usmdp.lbl.gov/scpack-code/