Effects of saturation, harmonics& solid iron rotor/pole shoe in SM

Day 14

ILOs – Day14

- Understand the effects of magnetic saturation on generalized analysis of electric machines
- Outline the methods for analysis of machines considering saturation:
  - Linearized equivalent circuit
  - Piece-wise linearized more
  - FEM
  - FDM

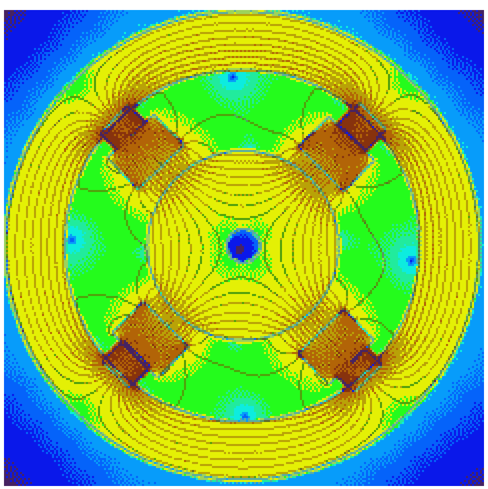
Effects of saturation

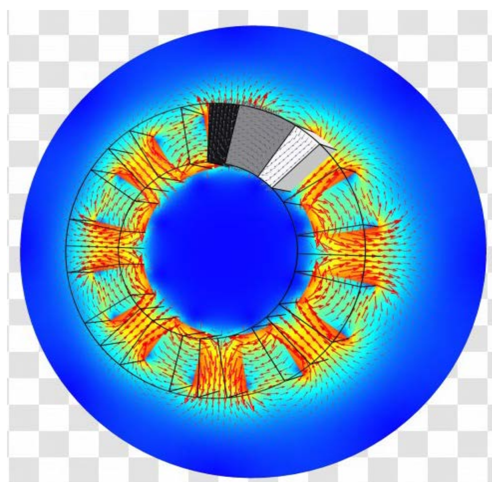
- **The generalized theories developed in Chapter 1 depend on the assumptions**
  - The magnetic material is unsaturated
  - All fluxes are proportional to the currents producing them

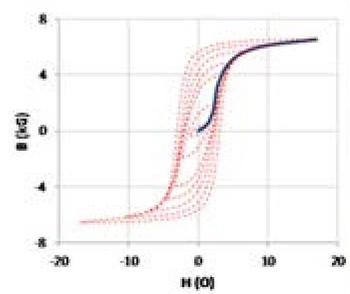
$$\phi = \frac{MMF}{\text{Reluctance}} = \frac{Ni}{S}$$

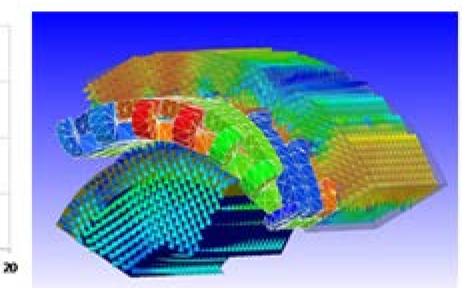
Effects of saturation

- **In reality, however, all magnetic materials get saturated if the exciting current is too high**
  - A complete determination of the effect of saturation would require:
    - Mapping of flux over the whole region in the machine at every instant due to any set of currents
    - This requires the help of computer based simulations
      - ANSYS
      - Simcenter MAGNET – Siemens
      - MagNet
      - COMSOL



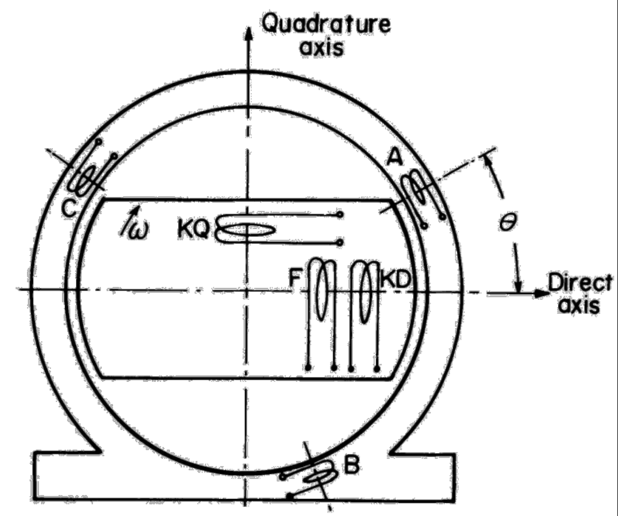






Mapping of flux over the whole region

- **In 3-phase synchronous machine, mapping of flux:**
  - 3 stator currents and 3 rotor currents
  - 6×6 matrix
  - 19 independent inductances
    - Each function of 6 currents and rotor position
- **Detailed calculation is very complicated**

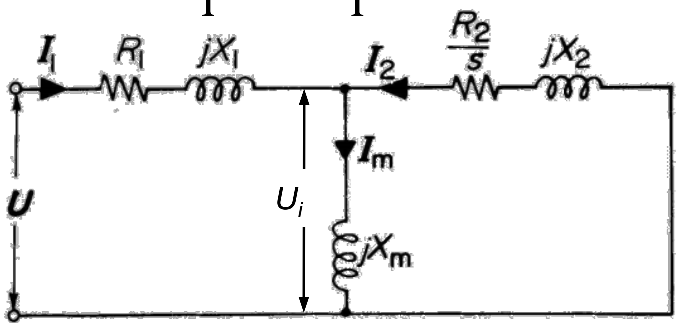


	a	b	c	f	kd	kq
$\mathbf{Z} = a$	$R_a + p(A_0 + A_2\cos 2\theta)$	$p\left[-B_0 + B_2\cos\left(2\theta - \frac{2\pi}{3}\right)\right]$	$p\left[-B_0 + B\cos\left(2\theta - \frac{4\pi}{3}\right)\right]$	$pC_1\cos\theta$	$pD_1\cos\theta$	$pD_1\sin\theta$
b	$p\left[-B_0 + B_2\cos\left(2\theta - \frac{2\pi}{3}\right)\right]$	$R_a + p\left[A_0 + A_2\cos\left(2\theta - \frac{4\pi}{3}\right)\right]$	$p(-B_0 + B_2\cos 2\theta)$	$pC_1\cos\left(\theta - \frac{2\pi}{3}\right)$	$pD_1\cos\left(\theta - \frac{2\pi}{3}\right)$	$pD_1\sin\left(\theta - \frac{2\pi}{3}\right)$
c	$p\left[-B_0 + B_2\cos\left(2\theta - \frac{4\pi}{3}\right)\right]$	$p(-B_0 + B_2\cos 2\theta)$	$R_a + p\left[A_0 + A_2\cos\left(2\theta - \frac{2\pi}{3}\right)\right]$	$pC_1\cos\left(\theta - \frac{4\pi}{3}\right)$	$pD_1\cos\left(\theta - \frac{4\pi}{3}\right)$	$pD_1\sin\left(\theta - \frac{4\pi}{3}\right)$
f	$pC_1\cos\theta$	$pC_1\cos\left(\theta - \frac{2\pi}{3}\right)$	$pC_1\cos\left(\theta - \frac{4\pi}{3}\right)$	$R_f + L_{ff}p$	$L_{fkd}p$	
kd	$pD_1\cos\theta$	$pD_1\cos\left(\theta - \frac{2\pi}{3}\right)$	$pD_1\cos\left(\theta - \frac{4\pi}{3}\right)$	$L_{fkd}p$	$R_{kd} + L_{kkd}p$	
kq	$pD_1\sin\theta$	$pD_1\sin\left(\theta - \frac{2\pi}{3}\right)$	$pD_1\sin\left(\theta - \frac{4\pi}{3}\right)$			$R_{kq} + L_{kkq}p$

- 3-phase armature winding on stator
- Field winding F on rotor
- Damper winding denoted by KD & KQ in rotor

Effects of Saturation: Simplified method

- **Simplified methods for considering saturation:**
  - Assume that only one parameter is variable and that it varies with only one current
  - Example: Equivalent circuit of induction motor:



$$U = U_i + (R_1 + jX_1)I_1$$
$$0 = sU_i + (R_2 + jsX_2)I_2$$
$$I_m = I_1 + I_2$$
$$U_i = jX_m I_m$$

Eliminating U_i and I_m we get the two voltage equations:

$$\begin{bmatrix} U \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j(X_m + X_1) & jX_m \\ jsX_m & R_2 + js(X_m + X_2) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

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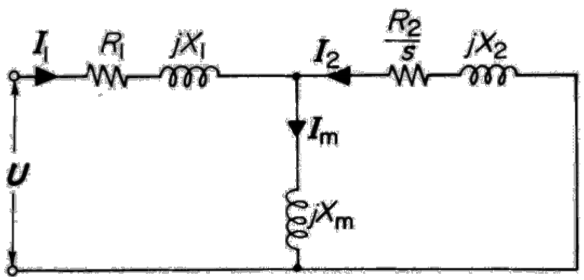
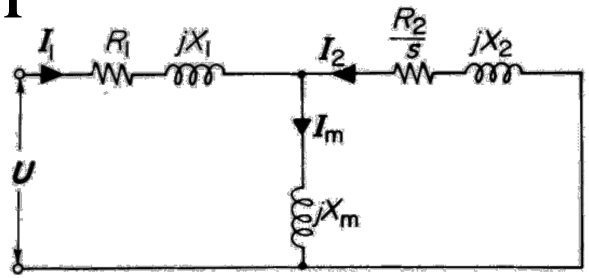


$$\begin{bmatrix} U \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j(X_m + X_1) & jX_m \\ jsX_m & R_2 + js(X_m + X_2) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

  - The total flux is separated into a magnetizing flux and two leakage fluxes
  - It can be assumed that the magnetizing reactance X_m is a function only of the magnetizing current
  - While the leakage reactances (X_1, X_2) are constants
  - Such a method has been applied successfully to the calculation of characteristics of an induction motor
  - Similar assumptions are used for the method of 'saturated reactance' for synchronous machines

Effects of Saturation: Simplified method

- **Simplified methods for considering saturation:**

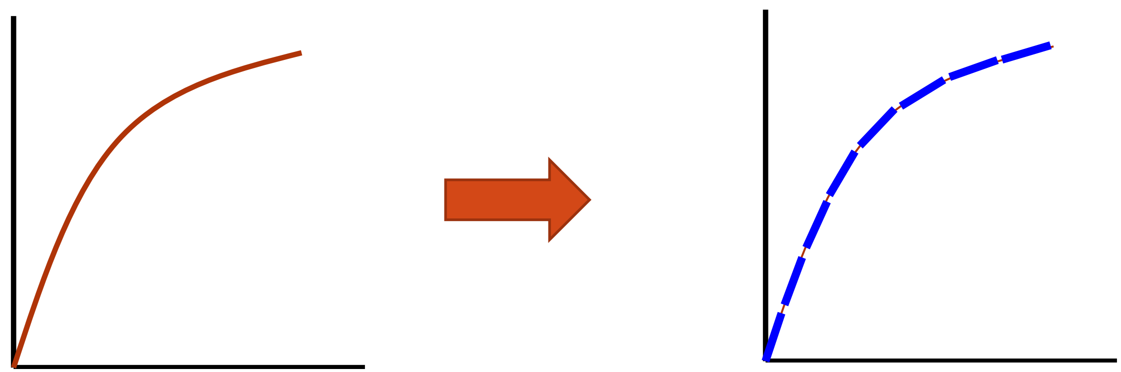


$$\begin{bmatrix} U \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j(X_m + X_1) & jX_m \\ jsX_m & R_2 + js(X_m + X_2) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

- This method works well till the currents rise to high values
- It is inaccurate when the currents are high enough to saturate the leakage flux paths
- For example, leakage reactance of an induction motor during starting at full voltage (high starting current) is different from than during normal running (low current)
- Any variation in the values of leakage reactance also affect the magnetizing reactance value since they pass through the same iron path

Effects of Saturation: Piece-wise linearization

- **Simplified methods for considering saturation:**
  - Thus saturation effect can not be fully analyzed using the circuit equations
  - Generalized theory can be used in such cases by assuming ***piece-wise linear models*** (curve represented by linear segments)



Non-linear saturation curve   Piece-wise linear curve

  - Incremental values of flux can be obtained from such piece-wise linearlized saturation curves
  - Solution to saturation effect can be better represented by such a linear generalized theory than that obtained from the linear equations

Effects of Saturation: Numerical techniques

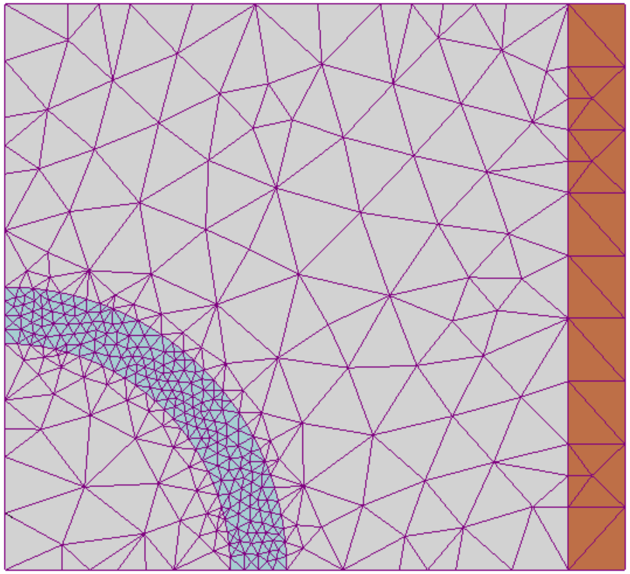
- **Detailed methods for considering saturation:**
- Using computer based simulation packages it is possible to obtain a more accurate solution by computing the flux distribution in detail
  - Finite Element Method (FEM)
  - Finite Difference Method (FDM)

Effects of Saturation: FEM

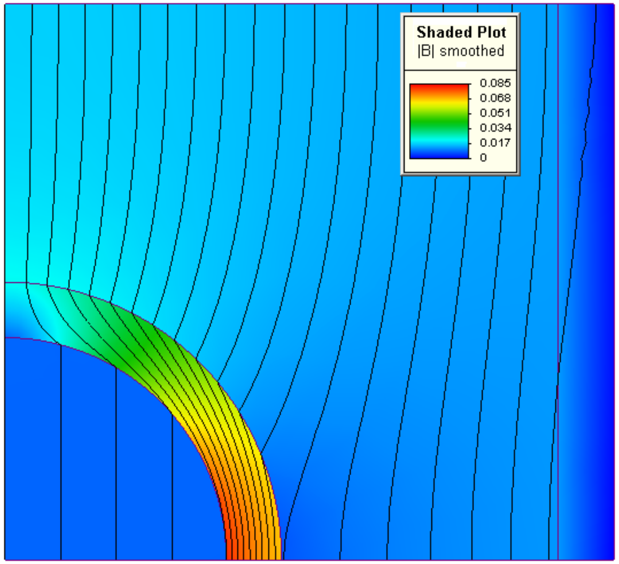
- **FEM:**
  - The finite element method is a numerical method that is used to solve boundary-value problems characterized by partial differential equations and a set of boundary conditions
  - The FEM subdivides a large system into smaller, simpler parts that are called finite elements
  - This is implemented by the construction of a mesh of the object
  - The differential equation is applied to each of the single element domains
  - Set of linear equations is obtained for each element in the discretized domain
  - Algebraic equation sets in steady-state problems are solved using numerical linear algebra methods
  - Differential equation sets in transient problems are solved by numerical integration using standard techniques such as ***Euler's method*** or the ***Runge-Kutta method***.

Effects of Saturation: FEM

- **FEM:**



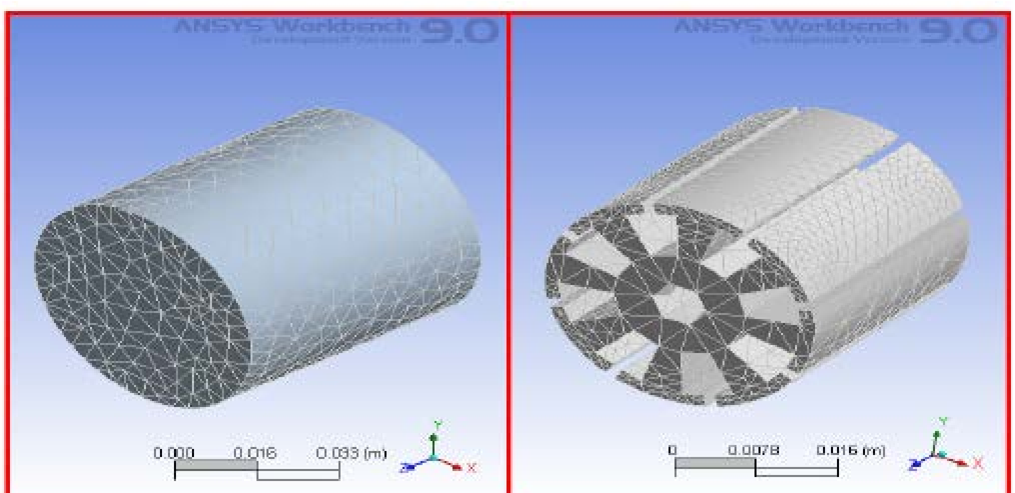
FEM mesh created for finding a solution to a magnetic problem using FEM software

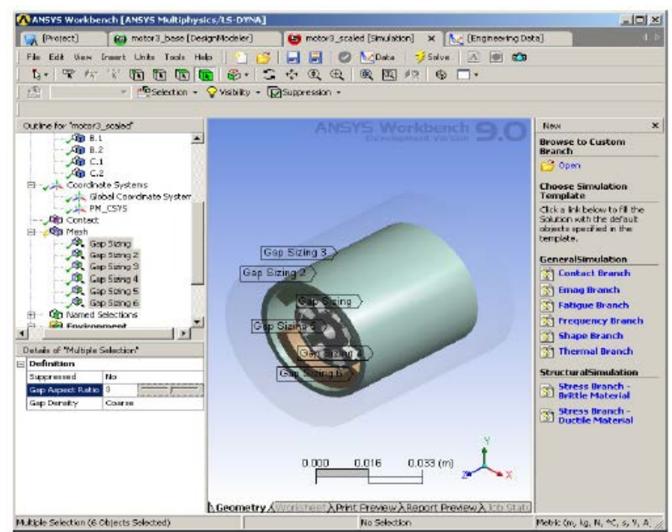


FEM solution to the problem The color represents the amplitude of the magnetic flux density

Effects of Saturation: FEM

- **FEM:**
  - The ANSYS program is based on the finite element method (FEM) for solving Maxwell's equations
  - ANSYS can be used for investigation of the magnetic field distribution
    - magnetic flux density, the magnetic field intensity and the magnetic vector potential etc.
    - Input data include defining the geometry, material properties, currents, boundary conditions, and the field system equations
    - The computer performs numerical solution of the field equation and output the desired parameters



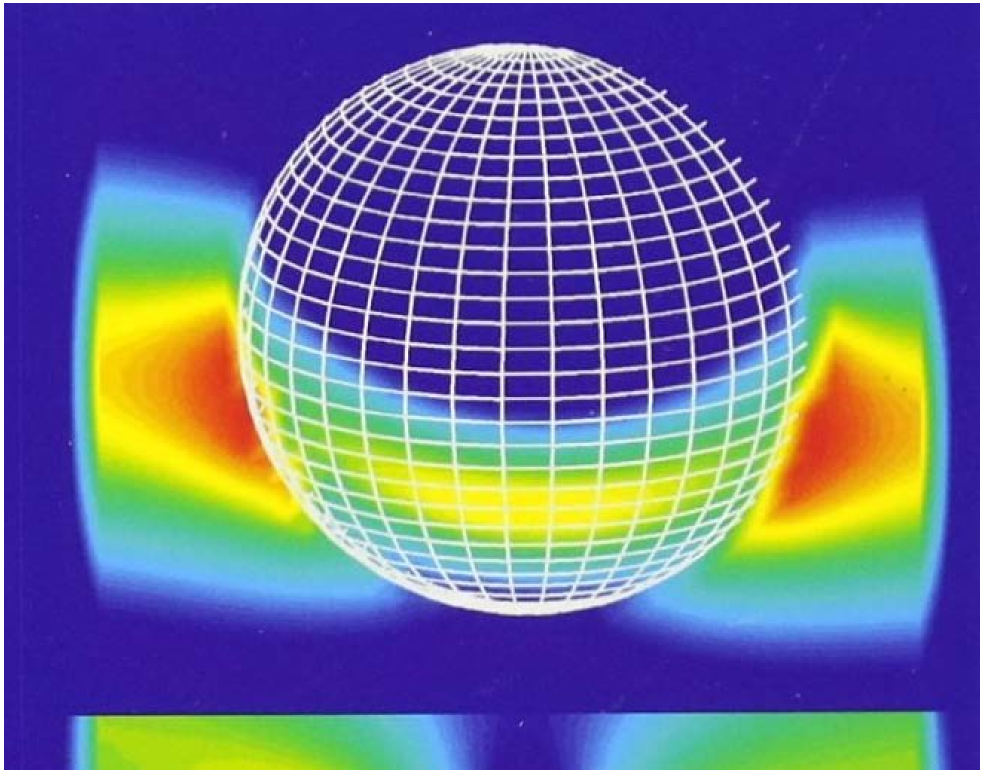


Effects of Saturation: FDM

- **FDM:**
  - The finite difference method is a powerful numerical method for solving partial differential equations
  - In applying the method of finite differences a problem is defined by:
    - A partial differential equation such as Poisson's equation
    - A solution region
    - Boundary and/or initial conditions

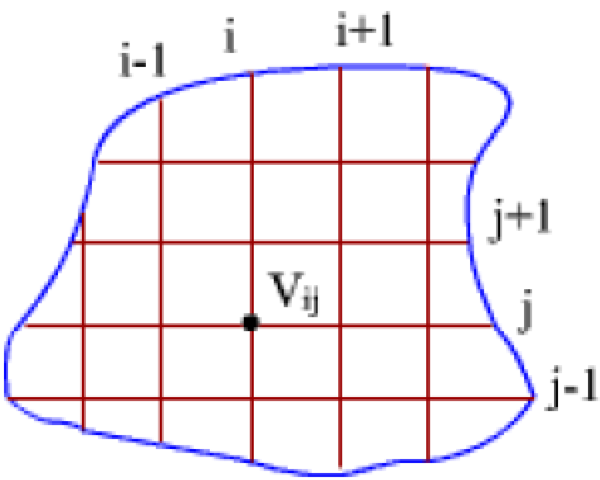
Effects of Saturation: FDM

- **FDM:**
  - An FDM method divides the solution domain into finite discrete points
  - Boundaries of the machine structure (solution space) is fit with small square, trapezoidal, or triangular elements

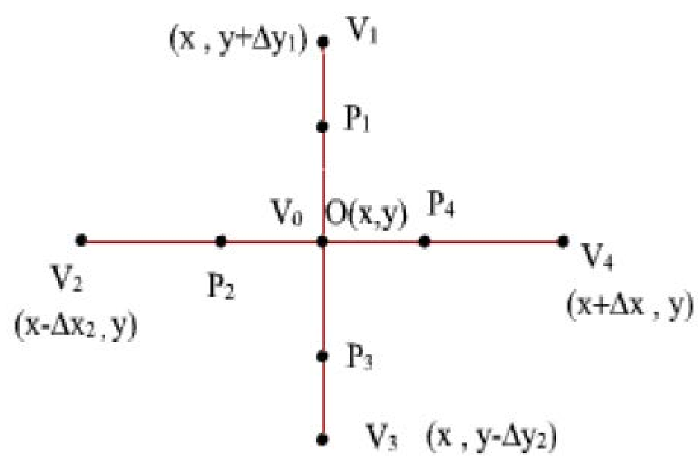


Effects of Saturation: FDM

- **FDM:**
  - The partial differential equations are replaced with a set of difference equations
  - If the discretization is made very fine, the error in the solution is minimized



Mesh created for finding a solution to a magnetic problem using FDM



Consider any node O (x,y)

$$\frac{\partial V}{\partial y} = \frac{V_1 - V_0}{\Delta y}$$

Replacing partial differential equations by difference equation (linearized)

Effects of Saturation: FDM

- **FDM:**
  - MATLAB can be used to execute FDM for magnetic field computations