Physics-Based Circuit Model for Nonlinear Magnetic Material Characteristics

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Motivation

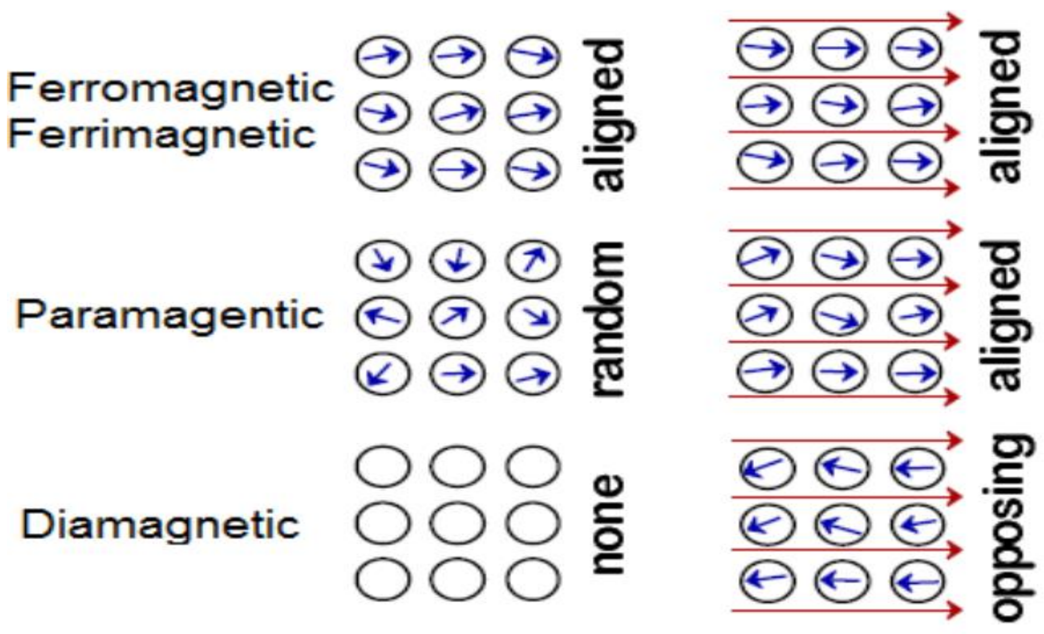
- Designing magnetic components, such as transformers and inductors, for high frequency power electronic applications is challenging due to the nonlinear behavior of the magnetic materials.
- These nonlinearities introduce complexities that hinder achieving good agreement between designs and prototypes, often leading to multiple trial-and-error in engineering practice.
- A comprehensive physics-oriented circuit model is essential for accurately predicting nonlinear characteristics, including core loss and permeability, of magnetic materials based on the fundamental dynamic magnetization behavior.

Physics behind Magnetization Dynamics

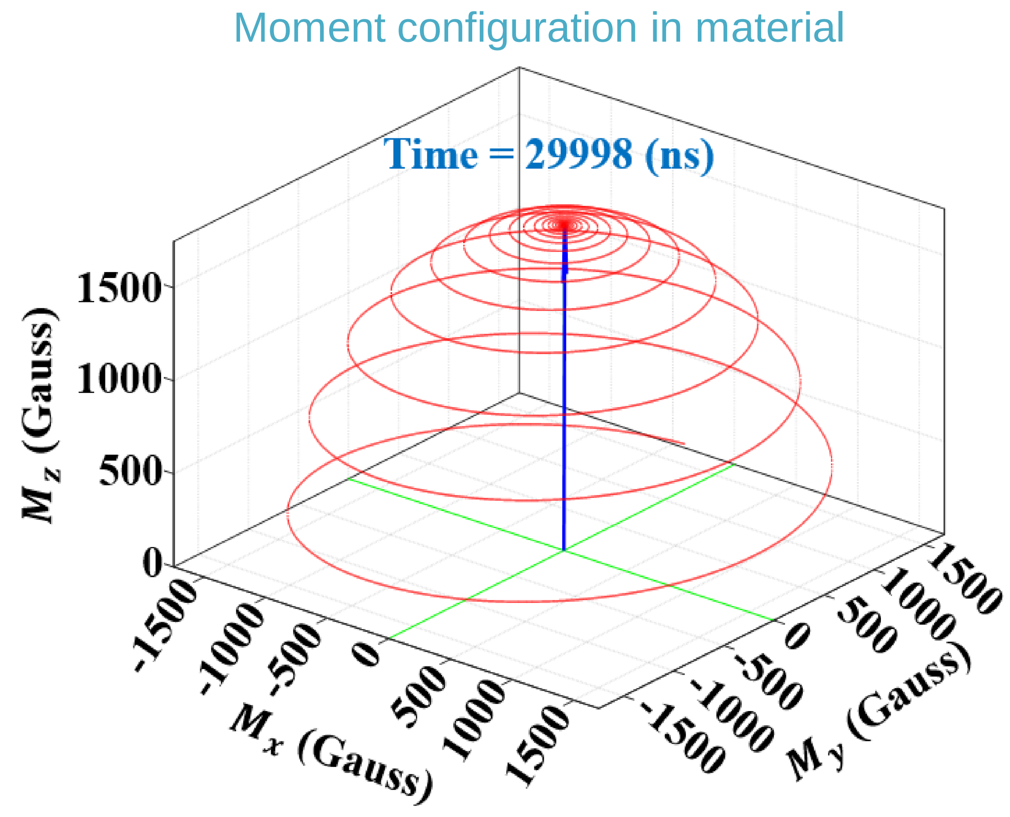
- Magnetic properties arise from electron spin configuration of the material.
- In materials with significant number of unpaired electrons, a net magnetic moment emerges, influencing magnetic permeability (μ), corresponds to the material's response to magnetization
- Magnetic materials at a specific temperature exhibit varying behaviors in response to external magnetic fields, depending on their moment configuration, impurities, crystallographic directions and so on.
- This process of magnetization dynamics can be compared to damped gyromagnetic precession described by Landau-Lifshitz Gilbert (LLG) equation as follows.

$$\frac{d\vec{M}}{dt} = -\mu_0\gamma\vec{M}\times\vec{H} + \frac{\alpha}{M_s}\vec{M}\times\frac{d\vec{M}}{dt}$$

- The inclusion of disparate inherent magnetic phenomenon along with the LLG equation can describe the magnetization dynamics within a material largely without the requirement of conventional & cumbersome iterative approaches.



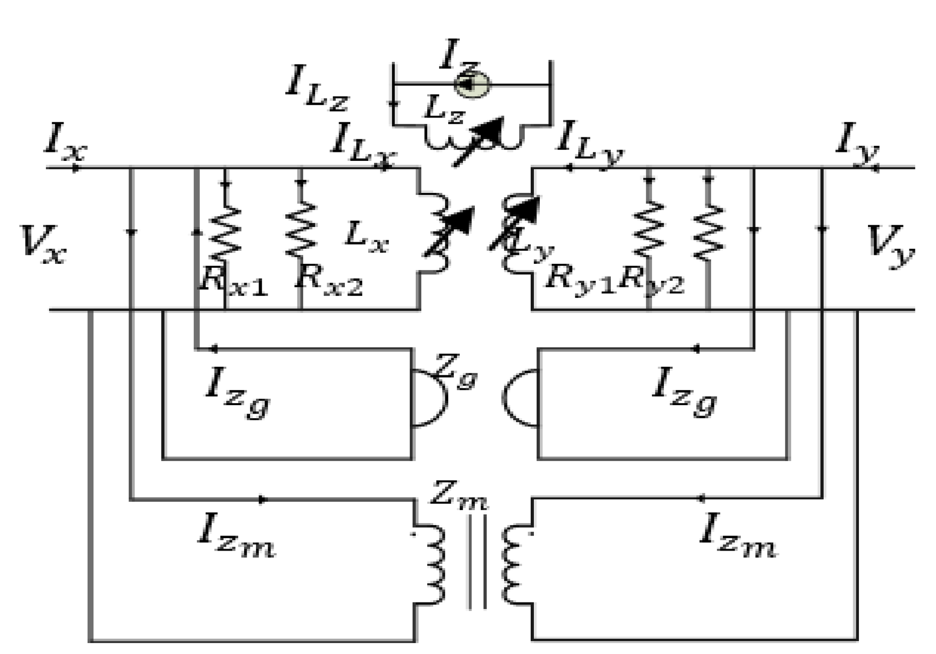
Moment configuration in material



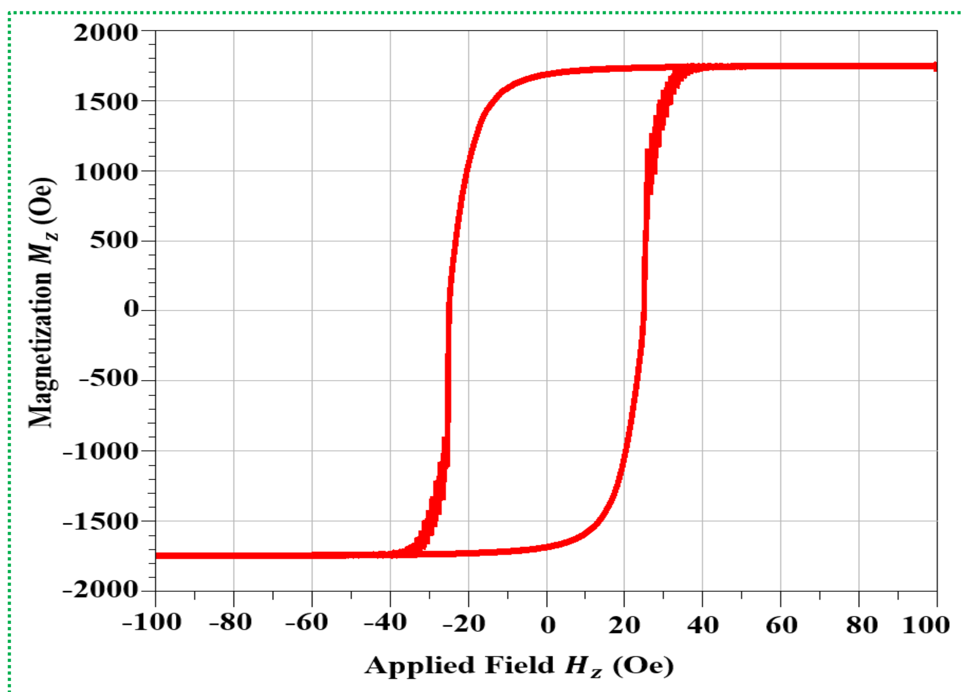
Precession of magnetic moment

Consideration

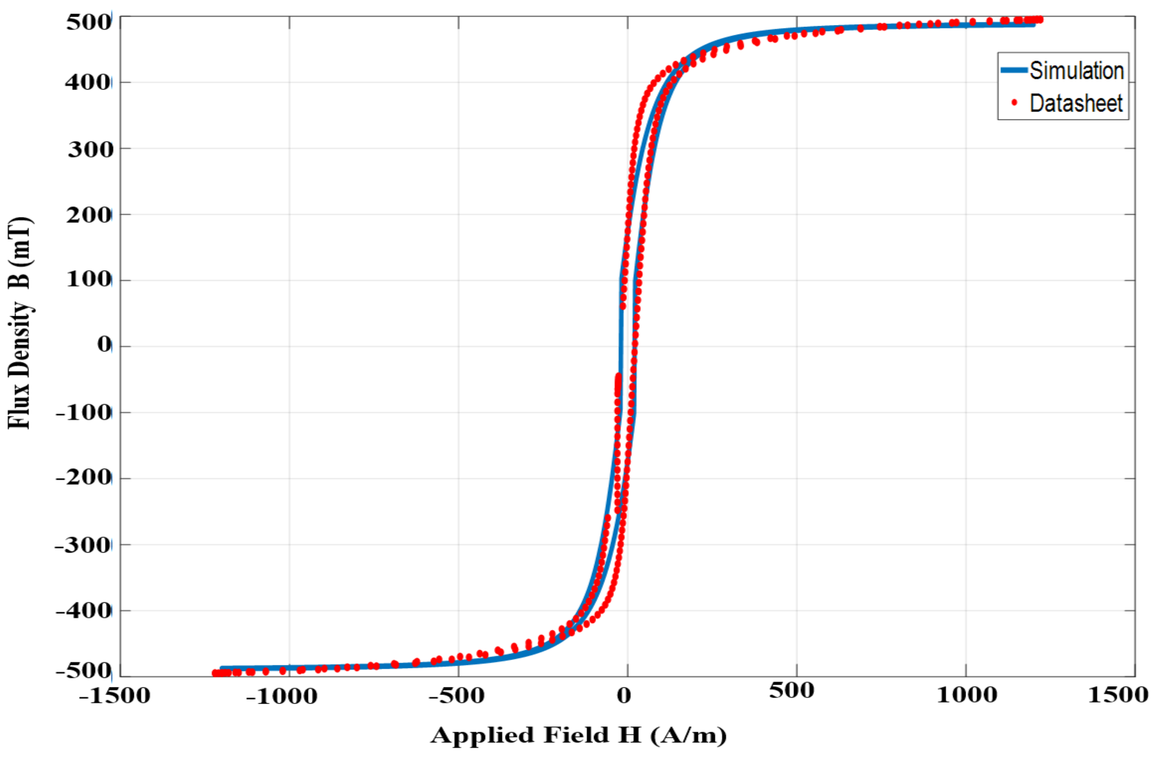
- Apart from the applied field & temperature, energy balance within a magnetic material, is largely dictated by, anisotropy, exchange, magnetostatic, magnetoelastic energy etc.
- To keep it simple and get started with, only the anisotropy energy is considered in this case where the anisotropy energy is calculated based on approximation of a single macro-spin unit (S-W particle).
- To disregard the effect of shape demagnetization and allow a continuous induction, the simulation is performed for a toroidal structure.



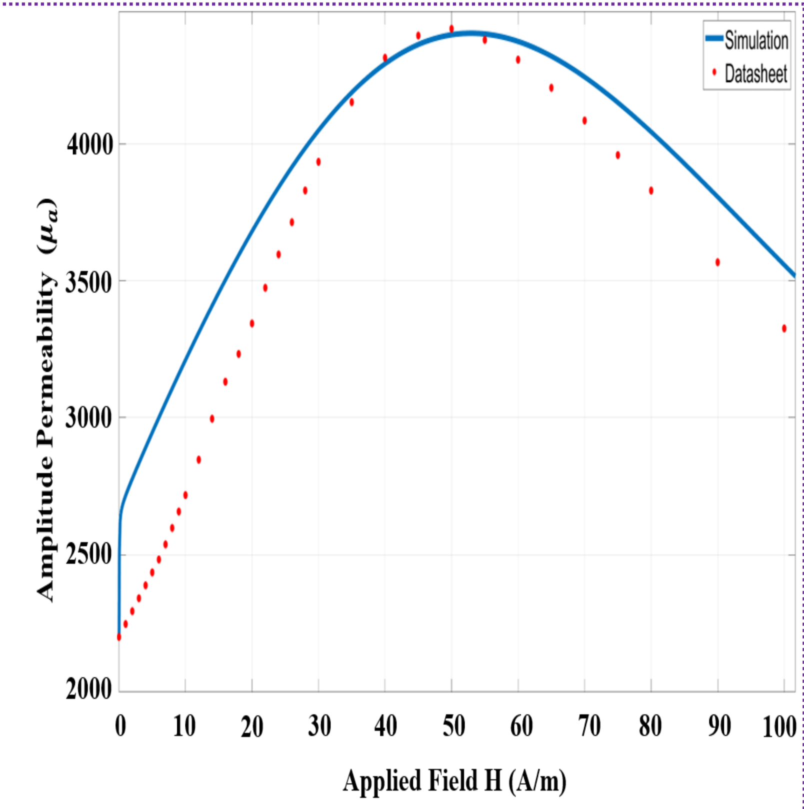
Equivalent Circuit Model



Obtained Hysteresis Loop



B-H loop of a Magnetic Material (N87).



Permeability profile in good agreement with material datasheet.

Modeling Approach

- LLG equation is derived to express the precession projection along different directions.
- The physical parameters such as magnetization, gyromagnetic ratio, damping factor, etc., are translated to equivalent circuit parameters.
- A three-port circuit configuration is established. The elements are mostly nonlinear in nature since they are dependent on field and magnetization components along different projections.
- The simulations are performed using ADS simulator.
- Upon establishment of circuit model, a hysteresis loop is obtained.
- Later, applied field angle with respect to anisotropy vector is tilted to match the hysteretic behavior of the experimented material.

Conclusion & Future Work

- The obtained results are in good agreement with the data found in the data sheet.
- The model shows great potential in optimizing magnetic components.
- The model is considered for a specific temperature.
- Incorporating other energy contributions and considering temperature variations will increase the model's robustness, enabling it to produce more feasible results

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