Energy losses in soft magnetic materials: an overview

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Energy losses are the chief technical parameter by which the properties of a soft magnetic material are evaluated. The variety of available materials and the related physical properties, the wide range of frequencies and excitation regimes involved in applications, and the complex unfolding of the magnetization process with applied fieldstrength and frequency, make the accurate experimental measurement and the general assessment of magnetic losses an especially complex problem. After many decades of investigative efforts, loss modelling is still a subject of debate, with new challenges posed by progressively extended fields of application, enticing the development of competing and somewhat contrasting theoretical approaches. Empirical-phenomenological models are sometimes preferred in the engineering context, although the computing burden might be relevant. The simplest approach to the loss at given magnetizing frequency and induction level is the one offered by the popular Steinmetz's equation, with its trail of fitting constants, variously modified and adapted to specific experimental circumstances. It has since long recognized, however, that quasi-static W_h and dynamic W_{dyn} contributions to the energy loss are better treated as separate quantities. In doing this decomposition, by maintaining a phenomenological approach, one can focus on a quasi-static model for W_h and postulate a certain frequency and peak induction dependence for the dynamic eddy-current fields. While in this way one can better emulate the material response, a firm theoretical ground to the whole phenomenology is achievable only by detailed physical analysis of the magnetization process, accounting for its complex intrinsically stochastic nature. This goal is remarkably accomplished in Bertotti's Statistical Theory of Losses (STL), where the concept of loss decomposition, hysteresis plus classical and excess components, emerges in a natural way from the statistical approach to domain wall motion and magnetization reversal. By combining rigorous physical derivation with intrinsic flexibility, the STL permits one to deal with complex excitation regimes, while not being limited to conducting materials, that is, to the treatment of eddy current losses. It has been extended, for example, to the broadband analysis of losses in soft ferrites. Instigated by increasing use of soft magnetic cores in high-speed electrical machines and power electronics, recent investigations are especially focused on high-frequency losses and non-sinusoidal regimes, where challenges are posed by the treatment of the skin-effect and of the dissipative mechanisms by spin damping.