

Instantaneous Loss Integration Method to Estimate AC Losses in Superconductors With Spatial and Time Harmonics

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Abstract—Estimating AC loss is an essential step in designing fully superconducting (SC) machines, which typically involves using analytical and Finite Element Analysis (FEA) models. Established analytical models are available for stationary sinusoidal and uniform rotating fields. But, the fully SC armature winding experiences a non-uniform rotating magnetic field that can result in varying losses. In this paper, we propose extended analytical methods to estimate AC losses in non-uniform rotating magnetic fields. Our proposed methods can refine the AC loss estimation process and improve the subsequent cryogenic load design. The significant advantage of our proposed method is the ability to capture the impact of AC losses due to varying field magnitude within a single cycle. We estimate losses for various scenarios and compare them to FEA analysis results to verify the accuracy of our model. We then experimentally validate the FEA models used in the analysis for uniformly rotating fields, which establishes the feasibility of our proposed models.

Index Terms—Superconducting, AC loss, analytical models, finite element analysis, harmonics, power law, SC machines.

I. INTRODUCTION

FULLY superconducting (SC) machines have great potential for large wind turbine applications [1], [2], [3], [4], [5] due to their low operating electrical frequencies, typically 0.1–6 Hz [3], [6], [7], [8], [9]. Superconductors experiencing alternating fields or currents generate thermal losses within the conductor, a phenomenon known as *ac losses* [10], [11]. Fully SC armature windings experience alternating fields and currents and thus generate ac losses. These losses must be removed from the windings to keep them below their critical surface. Therefore, estimating the ac losses and sizing adequate cryogenic cooling is the key step in fully SC machine design. Conservative ac loss estimation and subsequent cryogenic design can adversely impact the machine power density. Reliable loss estimation methods

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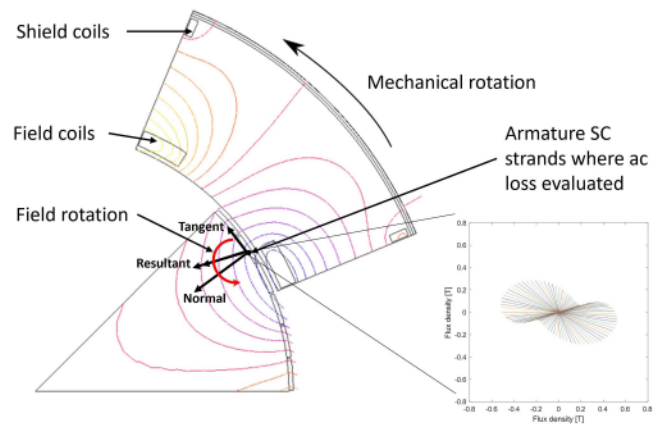


Fig. 1. Rotating field experienced by an armature winding.

can help machine designers to design electrical machines optimally, and this paper contributes to this effort. Well-established analytical models for a stationary sinusoidal field [12], [13], [14] and Uniform rotating magnetic field [11], [12], [15], [17], [17], [19] are available in literature. Capturing the additional loss due to sinusoidal magnetic field with ac ripples has been attempted by various researchers [20], [20], [22]. Harmonics present in the inverter-fed transport current also impact the ac losses. Research has been done on capturing these impacts on ac losses [23], [23], [24], [26]. Still, it remains a challenge for a non-uniform rotating magnetic field.

A 2-D cross-section of an actively shielded fully SC machine and the field experienced by its armature winding is shown in Fig. 1. The losses in each conductor are estimated using the field observed at the conductor location and then integrated over the volume of the armature winding to evaluate the total losses. Field winding arrangements create spatial harmonics in the air-gap field and contribute to the non-uniform air-gap fields. A comparison of the constant rotating field and non-uniform rotating field is shown in Fig. 2(a) and (b). When evaluating fully SC machine losses, the air-gap field is obtained from a detailed transient simulation, then analytical and FEA models are used on loss estimation [7], [27], [27], [28], [29], [31]. Carr's proposed ac loss models for stationary and uniform rotating fields to estimate losses in SC [12]. These models are used in [6], [9], [32], [33] to estimate machine losses. Wilson [13] proposed analytical models to estimate losses in multi-filamentary

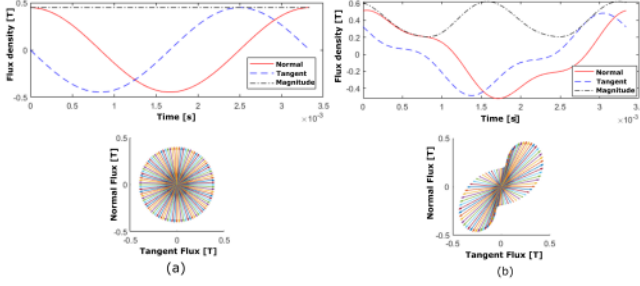


Fig. 2. Waveform of the applied tangential and normal field with the resultant field magnitude (a) uniform rotating field (b) non-uniform rotational field created by spatial harmonics.

conductors. These models estimate machine losses in [8], [34]. All these models assume uniform rotating fields; this assumption may result in an error in total estimated ac losses and subsequent cryogenic design. Integration of instantaneous losses and addition of harmonics methods are proposed in [35] to accommodate the influence of non-uniform rotating fields.

This paper presents an extension of the previously proposed ac loss models published in [35]. The extension includes detailed explanations, derivation of the general equation, derivation of well-established models from the proposed models, and experimental validation under a uniform rotating field. The application of the extended models is demonstrated by estimating losses in superconductors with simulated air-gap fields experienced by a Fully SC wind turbine armature winding. The results are compared against the FEA results obtained using Altair Flux software [36]. The FEA models employed in this comparison are experimentally validated in a low-frequency transverse uniform rotating field to establish the feasibility of the proposed models. For comparison, the paper also includes the harmonic addition method described in [35]. Several ongoing efforts exist to measure losses in HTS tapes under rotating magnetic fields [11], [37], [38], but loss prediction models have yet to be validated for MgB₂ conductors, and this paper contributes to this effort.

II. INSTANTANEOUS AC LOSS INTEGRATION METHOD

Using the Fourier transform, any applied transverse field to a conductor can be written as the summation of two perpendicular sinusoidal fields with a phase difference:

$$\vec{B} = \vec{x} \sum_i^n B_{xi,m} \sin(\omega_i t + \alpha_i) + \vec{y} \sum_i^n B_{yi,m} \cos(\omega_i t + \beta_i) \quad (1)$$

$$\omega_i = \omega_f i = 2\pi f i \quad (2)$$

where, $\vec{x}$ and $\vec{y}$ represents the two orthogonal axes considered, f is the fundamental frequency, ω_f if the fundamental angular velocity, i is the order of harmonics, $B_{xi,m}$ is the i th harmonic field amplitude chosen in the $\vec{x}$ direction, $B_{yi,m}$ is the i th harmonic field amplitude chosen in the $\vec{y}$ direction, α_i, β_i are the phase delay of the i th harmonics and t is the time. The addition of harmonic methods uses this approach to individually evaluate ac losses for each harmonic and add them to evaluate the total

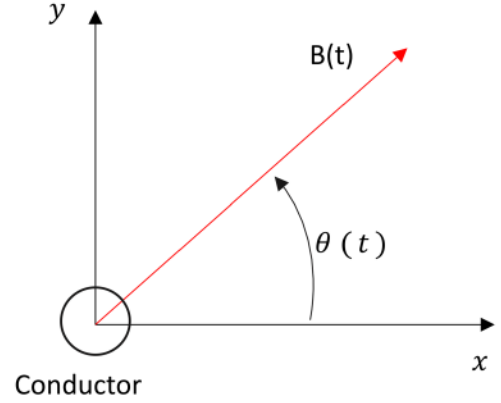


Fig. 3. Cartesian coordinates.

losses. The instantaneous loss method evaluates the losses at each instant and integrates over a period to calculate the average loss. For a circular wire with diameter d_f , cyclic hysteresis loss P_h generated for an external sinusoidal applied transverse field B is as follows:

$$\frac{P_h}{V} = \frac{2d_f J_c}{3\pi} \int_0^T |\dot{B}| dt \quad (3)$$

where, J_c if the critical current density at the applied field B and T is the period of the alternating field. In Cartesian coordinates, Fig. 3 shows a rotating non-uniform field $B(\theta(t), t)$, applied transverse to a conductor. This field can be represented by two orthogonal fields at a given instance as follows:

$$B(\hat{\theta}, t) = B \cos(\theta) \hat{x} + B \sin(\theta) \hat{y} \quad (4)$$

where, θ is the angle between the applied field direction and the chosen x direction, and B is the magnitude of the field at time t . The time derivative of this field $\dot{B}$ is as follows:

$$\dot{B} = (\dot{B} \cos(\theta) - B \dot{\theta} \sin(\theta)) \hat{x} + (\dot{B} \sin(\theta) + B \dot{\theta} \cos(\theta)) \hat{y} \quad (5)$$

The magnitude $|\dot{B}|$ of the time derivative can be evaluated as follows:

$$|\dot{B}|^2 = (\dot{B} \cos(\theta) - B \dot{\theta} \sin(\theta))^2 + (\dot{B} \sin(\theta) + B \dot{\theta} \cos(\theta))^2 \quad (6)$$

Applying the trigonometric equations to (6) and simplifying will result in the following:

$$|\dot{B}| = \sqrt{\left(\frac{dB}{dt}\right)^2 + \left(B \frac{d\theta}{dt}\right)^2} \quad (7)$$

where, $\frac{dB}{dt}$ is the time derivative of the field and $\frac{d\theta}{dt}$ is the angular derivative. Substituting (7) in (3) and a common equation for the transverse field can be obtained as follows:

$$\frac{P}{V} = \frac{2d_f J_c}{3\pi} \int_0^T \sqrt{\left(\frac{dB}{dt}\right)^2 + \left(B \frac{d\theta}{dt}\right)^2} dt \quad (8)$$

From (8), the loss equation for a transverse stationary field can be derived.

$$\frac{d\theta}{dt} = 0 \quad (9)$$

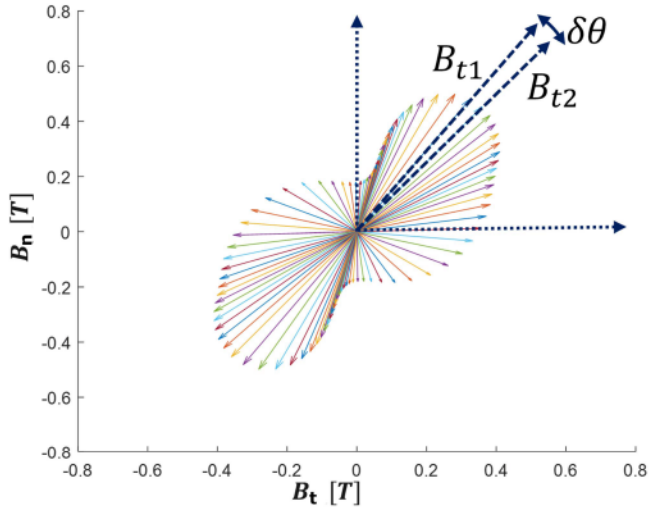


Fig. 4. Rotating non-uniform magnetic field.

$$\frac{P}{V} = \frac{2d_f J_c}{3\pi} \int_0^T \left(\left| \frac{dB}{dt} \right| \right) dt \quad (10)$$

$$\frac{P}{V} = \frac{2d_f J_c}{3\pi} \int_0^T (|\cos(\omega t)|) dt \quad (11)$$

$$\frac{P}{V} = \frac{8}{3\pi} B_m d_f J_c \quad (12)$$

Similarly, from (8), the loss equation for a uniform transverse rotating field can be derived.

$$\frac{dB}{dt} = 0 \quad (13)$$

$$\frac{P}{V} = \frac{2d_f J_c}{3\pi} \int_0^T \left(\left| B * \frac{d\theta}{dt} \right| \right) dt \quad (14)$$

$$\frac{P}{V} = \frac{2d_f J_c}{3\pi} \int_0^{2\pi} |B| d\theta \quad (15)$$

$$\frac{P}{V} = \frac{4}{3} B_m d_f J_c \quad (16)$$

This shows that the common equation derived in (8) can be used to derive the well-understood loss equations for two extreme cases: stationary and uniform rotating fields. In addition, the proposed equation can estimate the losses for any intermediate non-uniform field pattern resulting from combined rotating and stationary fields. Once the instantaneous losses are evaluated, integrating them over one period, the cyclic ac losses can be evaluated. Dividing that by the average time period gives an average ac loss for the SC wire in Watts.

For machine application, the air-gap field is extracted from transient FEA results based on the rotational field experienced by a conductor. Then the airgap field is modeled as two orthogonal magnetic fields, as shown in Fig. 4. Assume the consecutive vector fields at the airgap between δt interval is $B_{t1} = [B_{x1}, B_{y1}, 0]$ and $B_{t2} = [B_{x2}, B_{y2}, 0]$, then the $\frac{d\theta}{dt}$ and $\frac{dB}{dt}$ at time $t1$ can be

evaluated as:

$$\frac{dB}{dt} = \frac{|B_{t1} - B_{t2}|}{\delta t} \quad (17)$$

$$\frac{d\theta}{dt} = \frac{\delta\theta}{\delta t} \quad (18)$$

where, $\delta\theta$ is the angle between two consecutive vectors and can be evaluated as follows:

$$\delta\theta = \cos^{-1} \left(\frac{\hat{B}_{t1} \cdot \hat{B}_{t2}}{|\hat{B}_{t1}| |\hat{B}_{t2}|} \right) \quad (19)$$

Then, the hysteresis loss can be evaluated as:

$$P_{h,inst} = \frac{2J_c d_f}{3\pi} (|\dot{B}|) \quad (20)$$

$$P_h = \frac{1}{T} \sum P_{h,inst} * \delta t \quad (21)$$

Similarly, the eddy-current loss can be evaluated as

$$P_{e,inst} = \frac{1}{16} \sigma (|\dot{B}|)^2 D_o^2 \quad (22)$$

$$P_e = \frac{1}{T} \sum P_{e,inst} * \delta t \quad (23)$$

where, D_o is the conductor diameter, σ is the conductivity of the metal matrix. Coupling-current loss can be evaluated as

$$P_{c,inst} = \frac{l^2}{8\pi^2} \sigma (|\dot{B}|)^2 \quad (24)$$

$$P_c = \frac{1}{T} \sum P_{c,inst} * \delta t \quad (25)$$

where, l is the twist pitch.

III. EXPERIMENTAL VALIDATION UNDER UNIFORM FIELD

Fully superconducting (SC) electrical machines utilize low AC loss MgB₂ conductors and operate with rotating magnetic fields ranging from 0.2 T to 1.5 T at 20 K. There are currently no experimental results available in the literature that validate analytical or finite element analysis (FEA) models under uniform or non-uniform rotating field conditions. In order to validate these models, it is necessary to measure AC losses experimentally in a uniform rotating field and compare the results against the proposed analytical and FEA models. Once validated, the FEA models can be used to verify non-uniform field cases. Fig. 5 illustrates the experimental setup for measuring AC losses. A two-pole rare earth permanent magnet (PM) rotor, as shown in Fig. 6, is used to create a uniform magnetic field of around 1 T within a 40-mm air gap. To prevent eddy current losses, MgB₂ wire samples are attached to a ceramic sample holder, which is then attached to a cold head to maintain the required temperature while the samples are placed within the rotor air gap. The PM rotor and samples are located in a stationary ultra-low vacuum chamber to avoid convection losses. A ferrofluid rotary coupler is used to rotate the PM rotor and apply the rotating magnetic field, with the field frequency being varied by adjusting the rotor's rotating speed. The AC losses in the MgB₂ conductor samples are measured using a heater-based calorimetric method. A heater is attached to the sample, allowing control of the heat load on

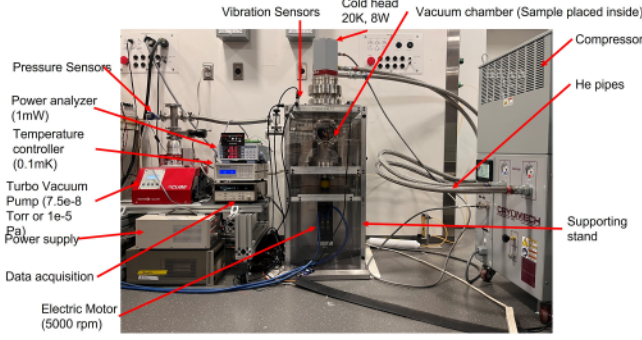


Fig. 5. Ac-loss measurement test setup.

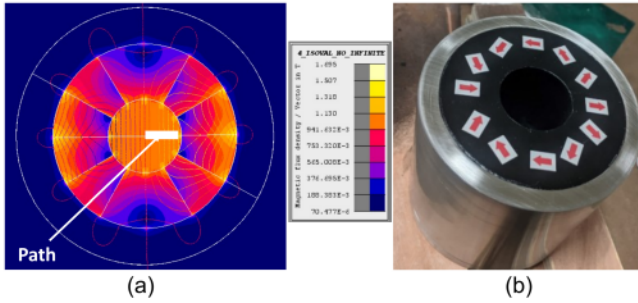


Fig. 6. (a) Flux density variation in the air gap. (b) Fabricated magnet rotor.

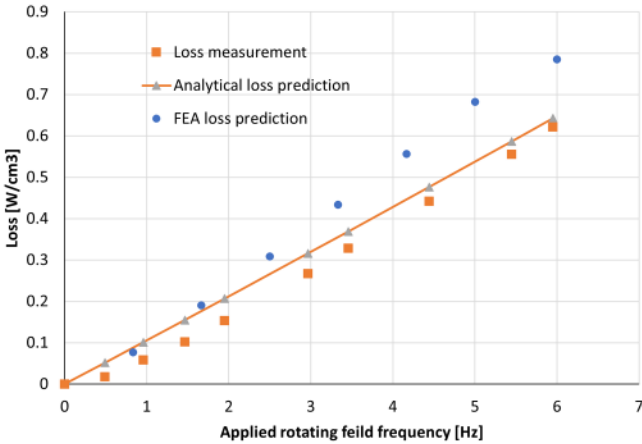


Fig. 7. Experimental Vs. simulation of ac loss for a multifilamentary conductor with varying field frequency.

the cryocooler and the cold-head temperature while operating the cold head in constant power mode. At stable conditions and idle operation, no losses are generated in the sample. However, when the rotating magnetic field is applied, additional AC losses cause an increase in the cold-head temperature. By reducing the heat dissipated in the heater, a constant temperature can be maintained. The reduction in heat load can be measured to estimate the AC losses generated in the sample. Fig. 7 compares the AC loss measurement results with the prediction for a commercially available MgB_2 conductor tabulated in Table I.

TABLE I
 MgB_2 CONDUCTOR DATASUPPLIER: HYPER TECH RESEARCH

Parameter	Multi [32] (machine)	Mono (analysis)	Multi [33] (Experiment)
SC outer diameter (D_o) [mm]	0.32	0.32	0.52
Filament diameter (d_f) [mm]	0.01	0.124	0.024
Number of filaments (n)	114	1	54
SC fill factor (λ)	0.15	0.15	0.12
Effective transverse resistivity [$\Omega\text{-mm}$] (ρ_e)	$1.25\text{E-}4$	$1.25\text{E-}4$	$1.25\text{E-}4$
Twist pitch [mm] (L)	5	-	10

FEA and analytical prediction closely match the experiment. This validates the FEA model used in the study.

IV. VERIFICATION FOR NON-UNIFORM FIELDS

To validate the accuracy of the proposed analytical models utilized for predicting non-uniform AC losses, experimentally validated finite element analysis (FEA) models from the Section III are used. FEA simulations are performed on monofilament and multi-filament conductors with specifications provided in Table I. Multi-filament conductors are utilized in machine design and experimental measurements, with a low AC-loss multi-filament conductor under development for the former and a commercially available multifilament conductor for the latter. To minimize numerical errors due to the small strand size in the multi-filament conductor simulations, a representative single-filament conductor is analyzed in non-uniform FEA simulations. This is a valid assumption given the dominant role of hysteresis losses in low-frequency wind turbine applications. Both conductors are designed to have the same fill factor and outer conductor diameter. Two scenarios are analyzed to examine the impact of non-uniform magnetic fields on AC losses. In the first scenario, the applied orthogonal field remains constant while the tangent-field amplitude is varied from half of the orthogonal field magnitude to its equivalent, resulting in a transition from non-uniform to uniform rotating fields as shown in Fig. 8. In the second scenario, a uniform rotating field is maintained while the third-harmonic amplitude is changed from zero to the first-harmonic amplitude, resulting in a transition from uniform to non-uniform rotating magnetic fields as shown in Fig. 9.

For comparison, ac losses are evaluated using the addition-of-harmonic method described in [35] and the instantaneous ac loss method and then compared with FEA. Fig. 10 compares results evaluated on a monofilament wire with a varying tangent field. Since field magnitude varies on non-uniform fields, conductor J_c and the ac losses also vary within a cycle. Instantaneous loss can capture this variation and predict the loss more accurately. As shown in Fig. 10, loss increases as the field become increasingly distorted, and the instantaneous loss method captures this. When the field becomes closer to uniform, it matches the loss estimation of the addition of the harmonics method. FEA results also capture this trend. Fig. 11 compares the ac losses evaluated using various proposed methods with the FEA on a monofilament conductor with varying third-order harmonic. Results show that the instantaneous loss estimation closely aligns with the FEA loss evaluation.

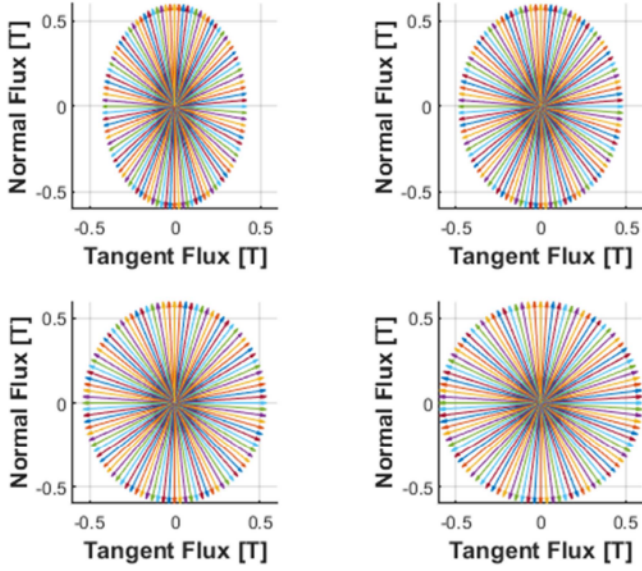


Fig. 8. Variation of tangent field (a) $\frac{B_t}{B_n} = 0.5$, (b) $\frac{B_t}{B_n} = 0.7$, (c) $\frac{B_t}{B_n} = 0.9$, (d) $\frac{B_t}{B_n} = 1$.

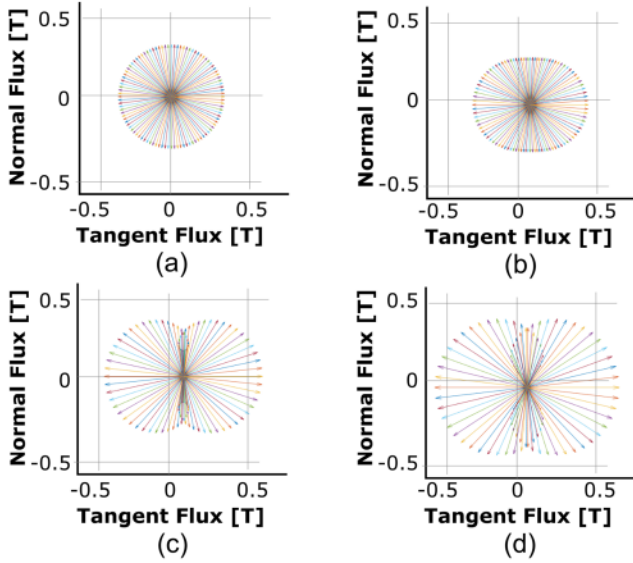


Fig. 9. Third-harmonic variation (a) $\frac{B_3}{B_1} = 0.01$, (b) $\frac{B_3}{B_1} = 0.25$, (c) $\frac{B_3}{B_1} = 0.5$, (d) $\frac{B_3}{B_1} = 0.75$.

Harmonic information obtained from a fully SC machine transient analysis is given in Table II. The following scenarios are considered to evaluate the losses on single and multi-filament conductors at various frequencies:

- Scenario 1: Assume a uniform rotating field.
- Scenario 2: Assume non-uniform rotating fields caused by phase-angle difference.
- Scenario 3: Assume non-uniform rotating fields caused by amplitude difference.
- Scenario 4: Assume non-uniform rotating fields caused by phase-angle and amplitude difference.

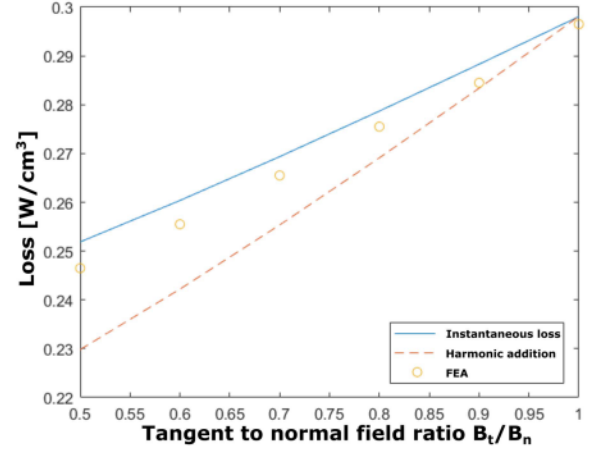


Fig. 10. Ac loss variation with tangent field at 6-Hz for a monofilament conductor.

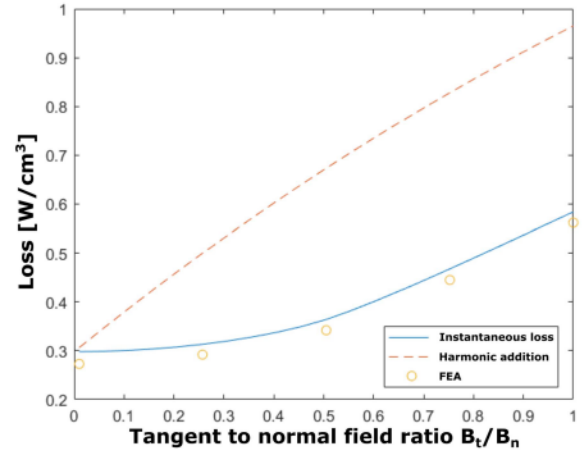


Fig. 11. Ac loss variation with third harmonic at 6-Hz for a monofilament conductor.

TABLE II
FIELD HARMONICS

n	f [Hz]	Normal B_m [T]	Phase delay $[\alpha]$	Tangent B_m [T]	Phase delay $[\beta]$
1	6	0.67	-23.52	0.335	24.5
3	18	0.447	11.98	0.447	101.96

- Scenario 5: Assume a non-uniform rotating field with first and third-order harmonics.

Fig. 12 provides the evaluated average loss components using analytical models and compares them against FEA losses. The results show that instantaneous loss evaluation closely matches the FEA simulation. The solid line shows the analytical ac loss estimation assuming a uniform rotating field. The deviation between the uniform field and the observed field ac loss estimation varies depending on the scenario. For example, for scenario 5, the uniform field assumption underestimates losses by 50% compared to the loss estimated using the observed field.

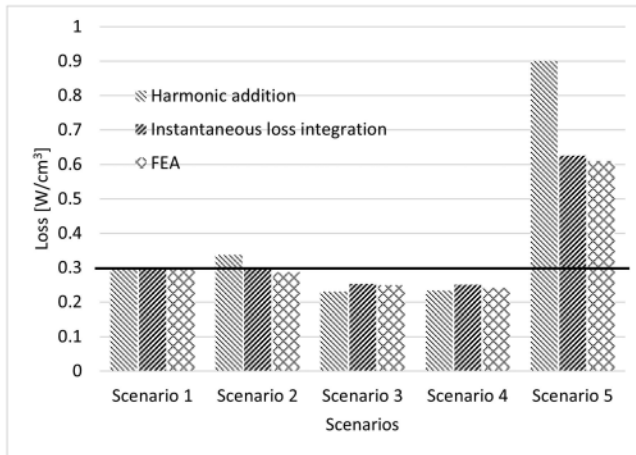


Fig. 12. Monofilament conductor average cyclic losses in W/cm^3 at 6-Hz.

V. CONCLUSION AND FUTURE WORKS

The estimation of AC losses using analytical models assuming a uniform rotating field in the air gap can result in significant deviation in the total AC loss estimation. To address this issue, analytical approaches for non-uniform fields have been introduced and verified using FEA tools. Two models have been compared, and the instantaneous AC loss estimation method has been found to closely match the FEA results compared to the addition-of-harmonics method. The accuracy of the proposed models has been validated using a high-precision AC-loss test setup to measure the AC losses in multi-filament MgB_2 conductors under a uniform rotating field. The experimental results have shown that the AC loss predictions from the analytical and FEA models closely match the measured data for uniform fields. This validates the FEA models used in the AC loss verification and establishes the fidelity of the proposed non-uniform application. In summary, this study provides a better understanding of the impact of a non-uniform rotating magnetic field on AC losses in MgB_2 superconducting armature windings and offers valuable insights for the design and optimization of superconducting electrical machines. Future works will include high-frequency loss prediction and validation.

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