MagNet Challenge 2023 Revisited: Beyond the Bounds of Equation-Based Core Loss Modeling

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***Abstract*—This work focuses on addressing limitations and improving MU's MagNet Challenge 2023 core loss model. MU's core loss model is presented and explained, which formalizes and standardizes the model. Then, key limitations detected after the results of the MagNet Challenge are discussed. Some implementation issues of the model are fixed, which improves the performance of the model. In addition, upgrades to the model based on physical insight and ties with previous works are made, further improving the performance of the model. At the end, the fixed and improved model is about 60 % better accuracy and 40 % lower number of parameters. The model is designed to ease its adoption, and steps to facilitate replicating this work are taken.**

Keywords—Core Losses, Ferrite, Magnetic Devices.

I. Introduction

When designing magnetic devices such as transformers and inductors, a correct estimation of the overall device losses is critical to guarantee a high efficiency and power density, more so in high frequency applications. When it comes to the losses of the device, this can be classified into two groups: winding losses and core losses.

Unfortunately, unlike the winding losses that are a well understood phenomenon, evaluating core losses is a difficult task, since relying on analytical approaches does not yield accurate results. Although empirical models are typically accurate enough for simple designs, the flaws of classical models show their limitations when it comes to high frequency designs. These are due to many parameters, such as temperature, complex waveforms (non-sinusoidal, extreme duty cycles), DC bias in the core, relaxation losses, limited available data, etc.

Addressing this problem, the MagNet Challenge, launched in 2023, aimed to catalyze innovation in data-driven magnetic material modeling. The organizers provided core loss data for 10 materials under different magnetic excitations, including sinusoidal and non-sinusoidal waveforms, waveforms with relaxation losses, data at different temperatures and data with DC bias. The dataset provided is one of the only resources with enough data to effectively develop and evaluate data-driven or analytical core loss models.

The MagNet challenge ended with 23 different submissions from teams all over the world [1]. The top-performing teams were recognized at APEC 2024, and all data, tools, and results were made publicly available. The performance of the models was evaluated based on two variables: the 95th percentile relative error of the models, and the size of the models (number of parameters). These might not be the optimal parameters to evaluate a core loss model but present a standard method to evaluate completely different models: black-box models (12/23 submissions), grey-box hybrid models (9/23 submissions) and white-box equation-based models (2/23 submissions).

One of the 6 awarded models, the model presented by the authors and hereby referred to as the Mondragon University's model (MU's model), was designed with the main objective of serving as an alternative candidate of the classically used Steinmetz based equation models. To do so, the model is based on pre-existing models, analyzing the limitations of its predecessors and turning the model based on the data from the MagNet database. This model is characterized by a low number of parameters, the relatively high accuracy, and the standardized definition of the parameters as demonstrated in Fig. 1.

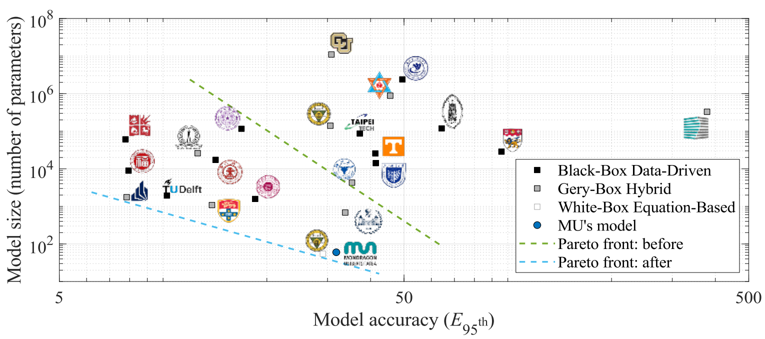

Fig. 1: Performance of the 23 models presented in the MagNet Challenge. Pareto fronts for core loss modelling before and after the MagNet Challenge are indicated.

Since the end of the MagNet Challenge, the model has received several updates improving its accuracy and reducing the number of parameters required, resulting in a more precise and simpler model. This paper documents the different improvements made to the model, explaining the inner workings of the model, demonstrating how the model applies to typical waveforms, and reporting the parameters and accuracies obtained for different materials.

II. Previous Mondragon University's Model

A. Foundation of MU's Model

As previously stated, MU's model presented at the end of the MagNet Challenge was designed to be a familiar alternative to the Steinmetz equation-based models. The first iteration of the model can be found in [2], which focused on improving the accuracy of classical Steinmetz based models (namely the improved Generalized Steinmetz Equation or iGSE [3]) with extremely low and high duty cycles. To do so, the Composite Waveform Hypothesis or CWH [4] is used, which previous works mentioned to be a promising candidate to evaluate the losses of triangular waveforms, although this claim was only proven in limited data. The model from [2] presented a deep demonstration of the CWH using all available data from the MagNet database, demonstrating the variability of the losses as a function of flux density and frequency.

Although the model in [2] is already a noticeable improvement on pre-existing methods, it had several limitations due to its reliance on high-degree polynomials to model what the model referred to as loss spaces. The most noticeable limitation was the quickly increasing error at the extremes of the loss space due to polynomial fitting, which means that the model cannot be used if extrapolation is required and thus is only applicable to a limited range of frequency and flux density.

To overcome this issue, MU's model eliminates its reliance on polynomial fitting by adopting a dual function-based model. This means that, instead of using complex functions as in [2], the proposed model uses effectively two simple functions to model loss spaces. Based on the classical Steinmetz theory of core losses, the core losses can be divided into two groups, hysteresis losses and eddy losses. According to the original work published by Steinmetz in 1980 [5], these can be expressed as two functions, with the hysteresis losses P_h being

$$P_h = \eta_h \cdot f \cdot B^{\beta} \tag{1}$$

and the eddy losses P_e being

$$P_e = \eta_e \cdot f^2 \cdot B^2, \tag{2}$$

where f denotes the frequency and B denotes the peak flux density on the core. The η and β parameters are constants derived from experimental data used to describe these loss functions, known as Steinmetz parameters. Note, the original Steinmetz publication [5] is often confused with what literature refers to as the Steinmetz Equation [6], which is a different model that simplifies both functions into a single function with the added α parameter where the core losses P are

$$P = \eta \cdot f^{\alpha} \cdot B^{\beta}. \tag{3}$$

B. MU's Model

Based on [5], the two functions used to model the losses are:

- **The quasi-static (qs) loss function**: dominant at low frequencies and/or magnetization rates, analogue to Steinmetz's hysteresis losses,

$$P_{qs} = k_{qs} \cdot \left|\frac{\Delta B}{\Delta t}\right|^{a_{qs}} \cdot B^{b_{qs}}. \tag{4}$$

- **Magnetization-rate (mr) loss function**: dominant at high frequencies and/or magnetization rates, analogue to Steinmetz's eddy losses,

$$P_{mr} = k_{mr} \cdot \left|\frac{\Delta B}{\Delta t}\right|^{a_{mr}} \cdot B^{b_{mr}} \tag{5}$$

In most cases, these two functions are enough to evaluate the losses of a non-sinusoidal waveform. To do so, the waveform is divided into different segments with unique magnetization rates dB/dt and the losses for each segment are evaluated independently with (4) and (5), and then the overall losses are obtained by combining the individual segments with a factor directly proportional to the duty cycle D

$$P = \sum\left[D \cdot \left(P_{qs} + P_{mr}\right)\right]. \tag{6}$$

This last step effectively applies the CWH previously mentioned, with a more detailed explanation found in [4]. A practical example of how to apply the model to a triangular and trapezoidal waveform is shown later in *Demonstration of MU's Model in Practical Cases*.

Note that this is not sufficient to evaluate all possible waveforms, since according to the improved improved Generalized Steinmetz Equation or i^{2}GSE [7] trapezoidal waveforms with relaxation segments display an additional core loss phenomenon that increases the overall losses, knows as relaxation losses. If a waveform of this type is to be evaluated, one must add an additional term for the relaxation effect. Based on the available data from the MagNet database, the simplified relaxation (rl) energy loss function

$$E_{rl} = k_{rl} \cdot t_{rl}^{a_{rl}} \cdot B^{b_{rl}} \tag{7}$$

is derived, obtaining the overall loss function as a function of the relaxation time t_{rl}. More detailed information on the relaxation losses is found in [7]. Then, the overall losses with the relaxation effect can be obtained by adding (6) and (7) together as

$$P = \sum\left[D \cdot \left(P_{qs} + P_{mr}\right)\right] + f_{rl} \cdot E_{rl}. \tag{8}$$

A practical example of how to apply the model to a trapezoidal waveform with relaxation losses is shown later in *Demonstration of MU's Model in Practical Cases*.

MU's model was not designed with sinusoidal waveforms in mind, since in most cases classical approaches are sufficient or available data from the manufacturer can be found for such cases. Nevertheless, the MagNet challenge required to evaluate losses in sinusoidal cases, thus a polynomial model similar to the classical Steinmetz equation (SE) was fitted and used to evaluate data in the case of sinusoidal waveforms. This added 6 parameters to the model.

In total, to evaluate the losses of a material at a given temperature 15 parameters are required (k_{qs}, a_{qs}, b_{qs}, k_{mr}, a_{mr}, b_{mr}, k_{rl}, a_{rl}, b_{rl}, and 6 parameters for sinusoidal waveforms). Since the MagNet database evaluated materials at 4 temperatures, a total of 60 parameters were presented in the MagNet Challenge per material. The overall results of the model compared to the rest of the MagNet Challenge participants is shown in Fig. 1. More relevant information of MU's model can be found on [8].

C. Demonstration of MU's Model in Practical Cases

For a more practical demonstration of how to apply the model to a typical waveform, the 3 cases from Fig. 2 are detailed. All 3 cases will apply to material 3C90 at 90 ºC. The required parameters for 3C90 are $k_{qs} = 1.70$, $a_{qs} = 1.24$, $b_{qs} = 2.06$, $k_{mr} = 1.84 \times 10^{-8}$, $a_{mr} = 2.49$, $b_{mr} = -0.38$, $k_{rl} = 1.75 \times 10^{6}$, $a_{rl} = 0.91$ and $b_{rl} = 3.08$. These and the parameters for other materials and temperatures can be found in the submitted final report at [8].

Note that the k parameters reported [8] are not the same as the ones used in this work due to different forms used for the loss functions. The forms used in this work are selected due to their similarity with the ones proposed by Steinmetz, thus the parameters k from [8] referred to as k^* must be converted as

$$k = \exp(k^*). \tag{9}$$

The first waveform is the case of an asymmetric triangular waveform with duty cycle $D = 0.2$ at $f = 199.17$ kHz and $B = 30.8$ mT. In this case, (6) is used since no relaxation losses occur. The model can be easily evaluated using element wise operators if the duty cycle is defined as $D = [0.2\ 0.8]$. The MATLAB code to evaluate a waveform of n segments without relaxation is shown in Code 1.

```
%% Waveform definition
D=[0.2,    0.8]
B=[  1,      1]* 0.0308
F=199.17e3
%% Evaluation of losses
Bp=max(B)
DBDt=2*B./(D/F)
P_qr= k_qs.* DBDt.^a_qs.*Bp.^b_qs
P_mr= k_mr.* DBDt.^a_mr.*Bp.^b_mr
P=sum( (P_qr+P_mr) .* D )
```

Code 1: MATLAB code to evaluate a waveform of n segments without relaxation losses.

The losses reported in the MagNet database in this case are $P_{\text{MagNet}} = 13.0\ \text{kW/m}^3$ while the losses predicted with the model are $P_{\text{model}} = 13.5\ \text{kW/m}^3$, resulting in an error of $E = +4.26\ \%$.

The second waveform is similar to the first case but has 4 unique segments. In this case, the duty cycles as defined in the MagNet database are $D_1 = 0.3$ and $D_2 = 0.4$, with a frequency of $f = 199.19$ kHz and $B = 69.5$ mT. Once again, Code 1 can be used to evaluate the losses, as long as the flux density B and duty cycle D are defined accordingly (in this case `D=[0.3,0.1,0.5,0.1]` and `B= [0.9,0.05,1,0.05]*0.0695`). The losses reported in the MagNet database in this case are $P_{\text{MagNet}} = 55.9\ \text{kW/m}^3$ while the losses predicted with the model are $P_{\text{model}} = 49.6\ \text{kW/m}^3$, resulting in an error of $E = -11.3\ \%$.

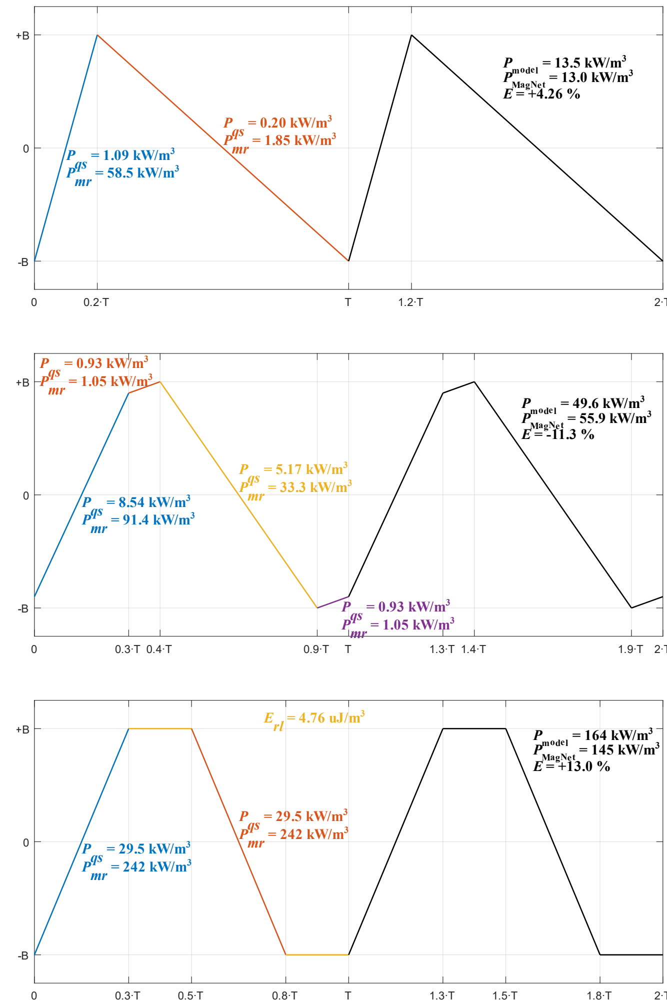

Fig. 2: Examples of using MU's model on different waveforms for material 3C90 at 90 ºC.

The last waveform is different to the previous cases, since in this case relaxation losses occur in segments 2 and 4. In this case, the duty cycles as defined in the MagNet database are $D_1 = 0.3$ and $D_2 = 0.3$, with a frequency of $f = 144.91$ kHz and $B = 97.3$ mT. For the relaxation losses Code 1 can be easily adapted for (8) with the calculation of the time per segment and relaxation loss function, which results in Code 2.

```
%% Waveform definition
D=[0.3,0.2,0.3,0.2]
B=[  1,  0,  1,  0]* 0.0973
F=144.91e3
%% Evaluation of losses
Bp=max(B)
t=(D/F)
DBDt=2*B./t
P_qr= k_qs .* DBDt.^a_qs .*Bp.^b_qs
P_mr= k_mr .* DBDt.^a_mr .*Bp.^b_mr
E_rl= k_rl .* t([2,4]).^a_rl .*Bp.^b_rl


P=sum( (P_qr+P_mr) .*D ) + f.*sum(Erl)
```

Code 2: MATLAB code to evaluate a waveform of n segments with relaxation losses.

The losses reported in the MagNet database in this case are $P_{\text{MagNet}} = 145\ \text{kW/m}^3$ while the losses predicted with the model are $P_{\text{model}} = 164\ \text{kW/m}^3$, resulting in an error of $E = +13.0\ \%$.

III. Revised Model

A. Limitations of the Model Fitting Algorithm

Although initial results for MU's model based on the 10 training materials appeared to indicate a high accuracy (95th percentiles of ~15 %), the results for the final 5 materials were noticeably worse (95th percentiles of ~31.8 %). Although a worst performance was expected, a factor of × 2 error indicates that the parameter fitting algorithm has trouble with the new datasets. By analyzing the final evaluation waveforms for the 5 materials that were published after the MagNet Challenge, clear discrepancies between the way waveform data for the initial 10 materials and final 5 materials were noticed.

By adapting the waveforms of the final 5 materials so that similar definitions to the initial 10 materials are obtained, the typical accuracy of the model for the final 5 materials was improved noticeably (95th percentiles of ~21.4 %), taking it closer to the expected results based on the initial results. The improvement can be seen in Fig. 3, named as MU's model + fix.

Still, for a specific material (Material D) the 95th percentile error was still excessively high, up to 40.1 %. A more detailed analysis revealed that this increased error was due to very limited relaxation data being available to fit the model (0 datapoints at 25 ºC). The utilized relaxation loss function (7) requires at least 3 data points to find a unique solution, which explains the extremely high errors that appear when evaluating waveforms with relaxation losses (errors up to +20098 % were identified in the evaluated data). This problem is not unique to MU's model, with other 20 teams also showing similar accuracies for Material D.

By leveraging relaxation data for Material D at different temperatures, the fitting algorithm is capable to obtain a set of relaxation parameters that are expected to be relatively close to the real ones. The accuracy of the relaxation loss functions in this case is expected to be noticeably worse than usual but should not generate the extremely high errors previously noticed. With this fix, the accuracy for Material D was improved down to 24.35 %. Overall, the typical accuracy for the final 5 materials was reduced to a 95th percentile of 18.3 % with bot fixes. The improvement can be seen in Fig. 3, named as MU's model + fit rules.

It is advised that the updated parameters found in [9] are used instead of the ones reported in [8] due to these fixes, especially for the final 5 materials.

B. Unification of Sinusoidal Losses

As previously mentioned in *MU's Model*, additional parameters were added for the MagNet Challenge so that sinusoidal losses could be evaluated. Since the physical phenomena governing core losses in sinusoidal and triangular waveforms are the same, sinusoidal losses should be evaluable with the same parameters as the rest of the waveforms. Evaluating this is important, since it demonstrates a unified model for sinusoidal, triangular and trapezoidal waveforms, which would indicate a good physical foundation for the model. Additionally, this would reduce the size of the model from 15 parameters to 9 parameters, which is a 40 % reduction on model size.

Since MU's model is intrinsically tied to the original Steinmetz's work for sinusoidal waveforms [5], this connection between sinusoidal and non-sinusoidal waveforms is expected to be reasonably accurate. In addition, the iGSE also presents a similar connection between sinusoidal and triangular waveforms [3]. By combining the findings from these works, the function for the quasi-static losses (4) can be transformed into

$$P_{qs} = 2^{2a_{qs}+b_{qs}} \cdot k_{qs} \cdot f^{a_{qs}} \cdot B^{a_{qs}+b_{qs}}. \tag{10}$$

For the magnetization-rate losses, the theoretical waveform coefficient $\pi/4$ for the eddy losses [10] must also be applied, so that expression (5) becomes

$$P_{mr} = \frac{\pi}{4} \cdot 2^{2a_{qs}+b_{qs}} \cdot k_{qs} \cdot f^{a_{qs}} \cdot B^{a_{qs}+b_{qs}}. \tag{11}$$

By adding both losses, the overall sinusoidal losses can be obtained. When applying this to the model slightly worse accuracy is obtained, which is expected due to a reduced number of parameters to fit the data. Still, this reduction in overall accuracy is very small, from a 95th percentile of 18.3 % to a 95th percentile of 18.8 %, while the number of parameters is reduced from 15 to 9. These changes can be seen in Fig. 3, with this model being named MU's model + unified.

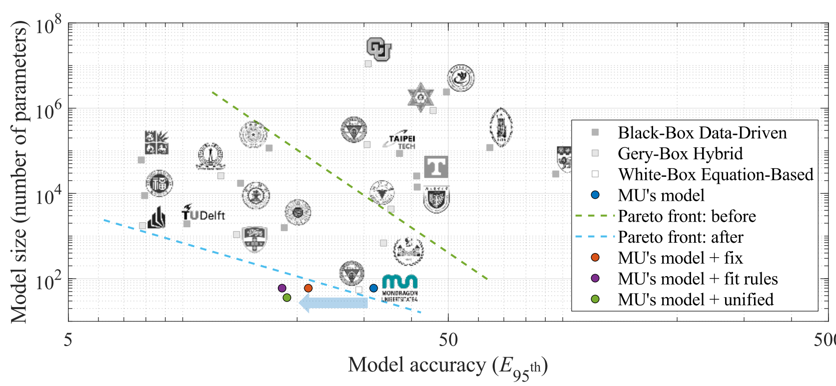

Fig. 3: Improvements in performance of the revised MU's model compared with the version presented on the MagNet Challenge.

DISCUSSION

Compared to the best performing model from the MagNet Challenge, Paderborn's model, the revised model trades accuracy (18.8 % VS 7.84 %) for model size (60 parameters VS 1755 parameters). Although a priory the trade appears to be an overall positive (higher reduction in size than lost in accuracy), in many practical cases, the size of the more accurate models might not be a major concern. Due to the capabilities of modern computers, the computation times of the heavier models can be low enough to justify their uses in design procedures.

Still, the physical explainability of the model, which is a key point that has not been mentioned yet, should not be discarded. Since the model has a high degree of explainability and is built using simple mathematical expressions that can be easily derived, it can be used to obtain analytical expressions for minimum loss designs.

In addition, the loss separation used to define hysteresis (quasi-static) and eddy (magnetization-rate) losses, the model offers a much higher potential to integrate other loss phenomena. One such effect is the addition of DC bias losses presented in the [11], where modified effective Steinmetz parameters are used to define changes in losses. Compared with [2], this work demonstrates that it models these effective Steinmetz parameters as a natural consequence of the loss separation into hysteresis and eddy losses instead of having to adapt the Steinmetz parameters for each frequency, flux density and duty cycle. Because of this, modelling effects such as the increase in losses due to DC bias can potentially be achieved in a simpler yet more intuitive way than [11].

DATA AVAILABILITY

All the core loss data used in this work is available in the MagNet database. The data can be accessed from the main MagNet Challenge GitHub [8].

Additionally, the different parameters for the MagNet Challenge MU's model can be found in [8]. The data for the revised MU's model can be found on the corresponding GitHub repository from [9]. It is recommended that the updated data from this last reference is used when adopting the model.

CONCLUSION

This work analyzes the MU's model presented in the MagNet Challenge, an equation-based core loss model characteristic by its reduced size (60 parameters per material) and relatively high accuracy (typical 95th percentile of 31.8 %).

The mathematical foundation of the model is detailed, relating the different loss functions to well-known physical phenomena and previous literature. The model is defined in a similar form to that of the typically used Steinmetz Equations family of equations, facilitating its adoption in typical transformer and inductor design workflows.

To facilitate the understanding of the model, practical cases for the evaluation of core losses for triangular and trapezoidal waveforms with and without relaxation losses are presented. The MATLAB code necessary to replicate the results is also given.

Still, several limitations were detected after the final evaluation data from the MagNet Challenge was made public. Most of these limitations were results of the final data format and model fitting algorithm. These problems are fixed and the new updated parameters for the model are available on [9]. In addition, the evaluation for sinusoidal losses has been integrated in the main model, reducing the number of required parameters from 60 parameters per material (for 4 temperatures) to 36 parameters.

These modifications and fixes reduce the typical error of the model by a factor of 40 %, while at the same time reducing the size of the model by 40 %, thus, the overall performance of the model (based on the MagNet Challenge performance indicators) is increased by a factor of $\times 2.8$.

Additional discussion regarding the physical foundation of the model and its potential to intuitively model DC bias core losses is also provided.

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