

Enhanced Magnetic Equivalent Circuit Modeling for Magnetic Flux Leakage Systems

Hasan Hüseyin Çelik¹

Abstract— Magnetic Flux Leakage (MFL) is a prominent non-destructive testing method utilized for the detection and characterization of defects in ferromagnetic materials. While the 3D Finite Element Method (FEM) provides high accuracy in MFL system design, it inherently introduces substantial computational and temporal costs. The conventional Magnetic Equivalent Circuit (MEC) method presents a computationally efficient alternative; however, it inevitably reduces accuracy due to its simplified representation of non-homogeneous flux density distributions. To mitigate this limitation, segmentation is conventionally applied solely along the longitudinal axis of the material. Nevertheless, the influence of inhomogeneity across the cross-section detrimentally impacts the precision of MEC analysis, particularly in thick-walled materials. This study proposes an advanced Segmented Magnetic Equivalent Circuit (SMEC) model for the design of MFL testing systems. The proposed SMEC model is predicated on applying segmentation that accounts for the non-homogeneous magnetic flux densities along both the length and the cross-section of the material. Furthermore, it models the behavior of magnetic leakage fluxes occurring within the air gaps of critical regions. The proposed SMEC and traditional MEC models were developed for a prototype MFL system, and their performances were comparatively evaluated against high-resolution 3D FEM simulations. The findings demonstrate that the SMEC approach significantly enhances modeling precision, achieving an accuracy increase of approximately 11% over the conventional MEC model, despite the use of a small number of segments.

Index Terms— Magnetic equivalent circuit (MEC), magnetic flux leakage (MFL), magnetic system optimization, non-destructive testing (NDT).

I. INTRODUCTION

As one of the leading non-destructive testing techniques, Magnetic Flux Leakage (MFL) plays a crucial role in detecting defects such as cracks, metal loss, and corrosion that develop over time in the structure of ferromagnetic materials [1-3]. In addition to infrastructures such as oil and gas pipelines, storage tanks, and railway lines, it has also become essential for the operational safety of modern power generation facilities [4-7]. In particular, the inspection of boiler tubes in thermal power plants, ferromagnetic heat exchanger networks in nuclear facilities, and steel wire ropes in wind turbines relies heavily on advanced MFL systems [8-10]. To ensure reliable inspection in these harsh environments, the level of magnetic flux density generated within the test material is critical. A reliable inspection requires a near-saturation flux density within the test material [11], [12]. At low flux densities, weak and unstable

signals are generated, and minor defects may remain undetected. Conversely, in the case of oversaturation, noisy and distorted defect signals are produced. This effect leads to erroneous interpretations during the defect characterization stage [13], [14]. Furthermore, near-saturation flux density does not exhibit a homogeneous distribution across the cross-section of the material [15]. This effect becomes more pronounced in thick-walled materials. Often overlooked in classical solution approaches, this phenomenon is a factor that negatively impacts measurement accuracy, particularly in MFL system design [16], [17].

Magnetic system analyses can be performed with high accuracy using simulation software based on the finite element approach, such as 3D FEM. However, such software concurrently entails high computational and temporal costs. This is due to the fact that magnetic analysis requires high-volume computational processes arising from a vast number of magnetic field lines and non-linear parameters. At this juncture, the Magnetic Equivalent Circuit (MEC) method offers a robust alternative with low temporal costs [18-20]. Although the method possesses lower accuracy compared to FEM analysis, it significantly reduces computational costs due to its lower model complexity [21], [22]. The MEC approach is widely utilized for design development, optimization, fault diagnosis, and predictive maintenance of magnetic systems in numerous industrial sectors alongside the MFL inspection industry. It can be stated that energy and power systems, automation and robotics, medical devices, and smart sensors are at the forefront of these fields. A review of the current literature reveals that the MEC approach is employed in research and applications involving wind turbines, generators, transformers, electrical machines, and vehicles [23-27].

Non-homogeneous magnetic flux densities occur within the material subjected to strong magnetic excitation in the MFL testing system. In the MEC method, these are modeled by reducing them into sub-sections that are assumed to be homogeneous. When this procedure is applied solely to the longitudinal dimension of the material, the inhomogeneity effect pertaining to the material's cross-section results in inadequate modeling. This study proposes the Segmented Magnetic Equivalent Circuit (SMEC) model developed for MFL testing system design utilizing the MEC approach. The proposed

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SMEC model is based on performing segmentation along both the length and the cross-section of the material in regions with high and non-homogeneous flux densities within the MFL testing system. Cross-sectional segmentation can facilitate a faster transition to high accuracy by encompassing the non-homogeneous distributions occurring in the cross-section. Furthermore, in the SMEC model, the magnetic flux behaviors of critical regions, such as air gaps, are also incorporated into the model. The performance of the SMEC was evaluated based on high-resolution 3D FEM simulations, and it was determined to provide approximately 11% higher accuracy compared to the classical MEC model.

II. MATERIALS AND METHODS

A. Fundamentals of the MFL

The MFL method operates on the principle of subjecting the test material to a high-intensity magnetic field, thereby inducing magnetic leakage fluxes in defective regions. For this purpose, a U-shaped yoke is constructed from a material with high magnetic permeability. By placing magnetic flux sources at the poles of the yoke in close proximity to the material, a near-saturation magnetic flux loop is established. A magnetic sensor is positioned at the magnetic neutral point between the poles. The mechanical system designed in this manner is translated across the material to perform the inspection process. As the material surface is scanned, the leakage fluxes originating from the defective regions are detected by the magnetic sensor, consequently acquiring defect signals. Fig. 1 illustrates the schematic structure of a prototype MFL test system and the acquired defect signal.

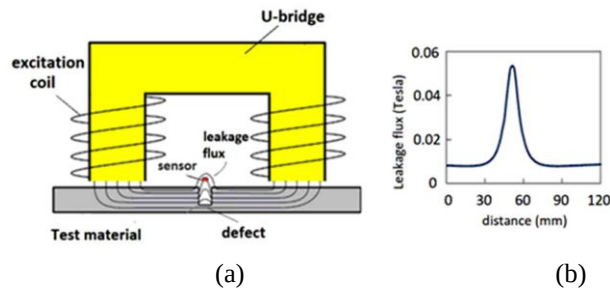


Fig. 1. MFL test system. (a) MFL test system structure. (b) An example of a defect signal.

In the MFL testing method, a more critical issue than merely detecting a defect is the highly accurate calculation of its physical parameters, such as width and depth, utilizing the acquired defect signal [28]. This situation stems from the inherently non-linear relationship between the defect geometry and the resulting signal. Unreliable or distorted defect signals lead to misidentifications, causing significant safety vulnerabilities in critical inspection procedures. One of the key factors influencing the defining characteristics of fault signals is the level of magnetic flux density in the test material. Other factors that affect this flux density level encompass the flux densities within the U-shaped yoke, magnetic excitation, the B-H curve of the material, and the dimensional parameters of the system. Furthermore, leakage fluxes propagating through the air medium also vary depending on the flux densities within the magnetic materials. All aforementioned factors exhibit non-linear relationships among themselves. Fig. 2(a) depicts the flux density distributions alongside the magnetic flux directions occurring in the magnetic materials via a color scale. Fig. 2(b) represents the leakage fluxes propagating through the air

medium. These visualizations were obtained from 3D FEM analyses conducted for a prototype MFL system. Fig. 2(c) shows the B-H curve of the material.

Upon examining the flux density distributions across the material cross-section in Fig. 2(a), it is observed that they are non-homogeneous and decrease radially outward from the inner channel region. In Fig. 2(b), it is observed that leakage fluxes are more intense in air regions adjacent to areas of high flux density, and vortex-like fluxes form depending on the system geometry. Due to their mitigating effect on the total flux within the material, the leakage fluxes in such critical regions must not be neglected during MEC optimization.

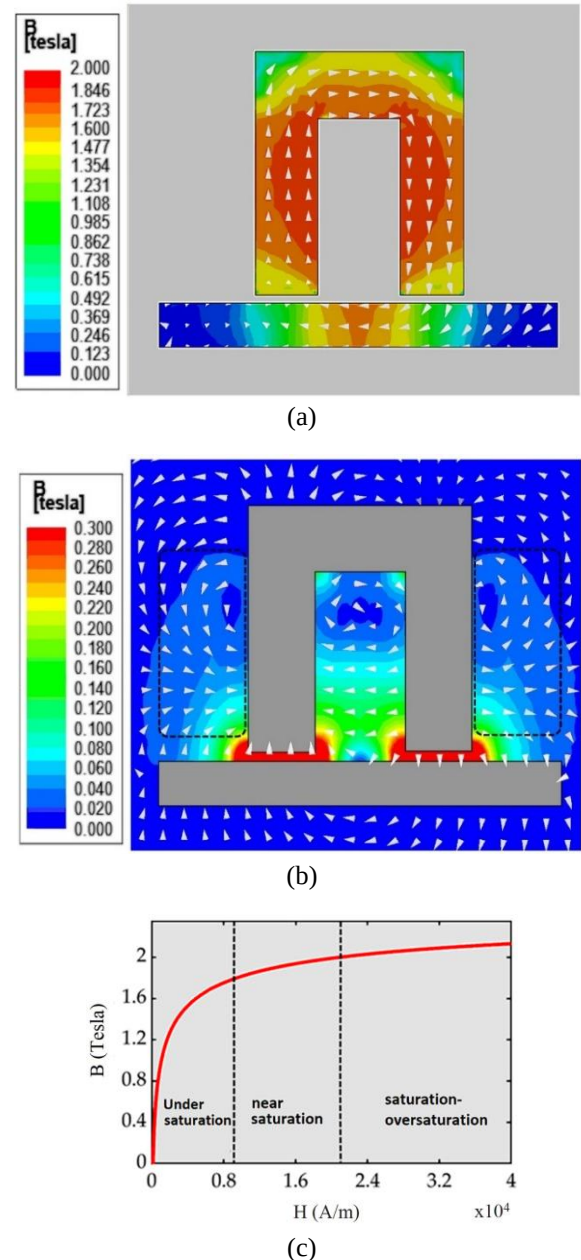


Fig. 2. (a) Magnetic fluxes and flux densities within the material, (b) Leakage fluxes and flux densities in the air medium, (c) The B-H curve of the material.

B. Conventional MEC Model of the MFL Test System

The MEC model is a tool utilized to correlate the magnetomotive force (F) with the number of coil turns (N) and the coil current (i) that generate the magnetic flux. Through this

approach, magnetic systems exhibiting inductive characteristics can be rapidly analyzed by drawing analogies to circuit analysis methods. In the MEC model, ferromagnetic elements are defined as non-linear reluctances (magnetic resistances) that vary depending on the magnetic flux passing through them. In contrast, the magnetic resistances of other media, such as air, are assumed to be constant if they are sufficiently small. These resistance values can be calculated using magnetic permeability based on Ampère's and Gauss's laws. The MEC model is also highly advantageous for calculating the magnetic field intensities within the system [29]. Fig. 3 illustrates the designed MFL system and the conventional MEC model representing this system. The dimensional parameters of the system are detailed in Table I.

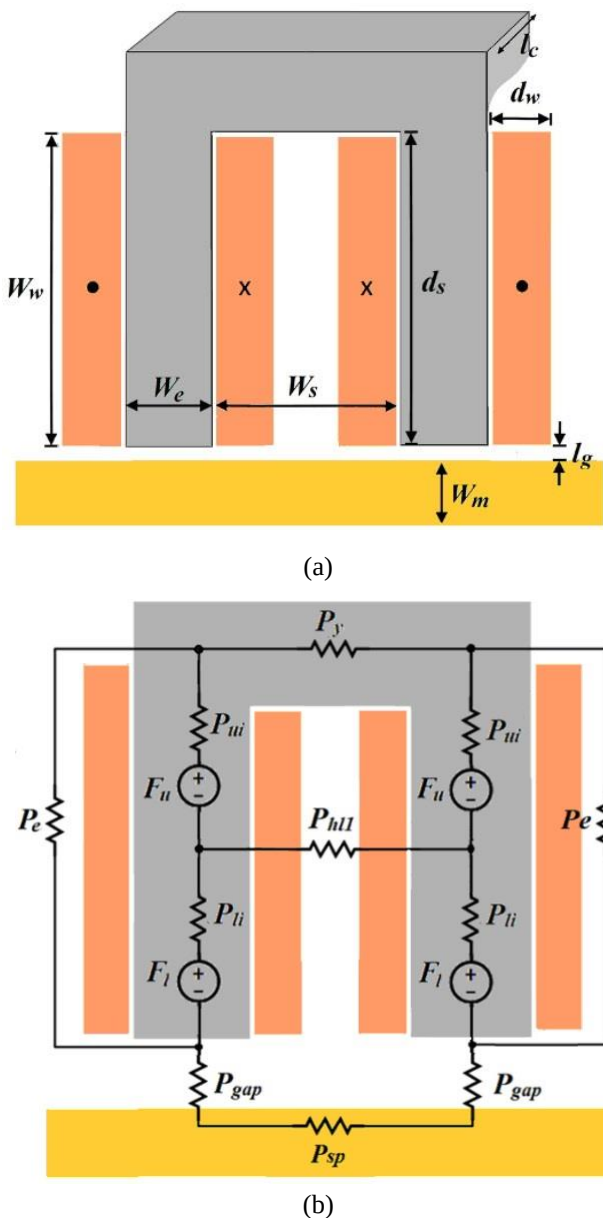


Fig. 3. (a) Descriptions of MFL test system dimension parameters. (b) Conventional MEC model of the MFL system.

The MEC model transforms the analysis of a complex magnetic system into a more readily solvable circuit analysis problem. Because reluctances vary depending on the magnetic flux, an iterative convergence algorithm is employed in this analysis process. The algorithm continues its iterations until the targeted error tolerance is achieved. Upon completion of this process, the

loop currents are obtained, and the magnetic parameters for all sections of the material are calculated.

$$F = Ni. \quad (1)$$

Here, N represents the number of turns of the excitation coil, and i denotes the value of the current flowing through the coil.

Table I. Description of the dimensional parameters.

Parameter Symbol	Description	Dimensions (mm)
W_s	Slot width	20
l_g	Air gap length	2
W_e	Yoke width	20
W_m	Specimen width)	5
dw	Winding width	4
Ww	Winding height	40
l_c	Yoke depth	72

The magnetomotive force (F) providing magnetic excitation to the system is expressed by the following equation:

C. 3D FEM Analysis of the MFL System

The MFL system, designed as a prototype in this study, was modeled in a 3D FEM simulation environment, and its high-resolution magnetostatic analyses were performed. All analyses were conducted using Ansys Maxwell software. To obtain highly precise and reliable results in the analyses, an adaptive mesh was applied. In accordance with the accepted standards for similar electromagnetic analyses in the literature, the maximum energy error for the convergence criterion was set to 1%, and the maximum number of consecutive solution steps (passes) was determined as 15. Consistent with the physical nature of magnetostatic analysis, a 'Balloon' boundary condition (acting as an open boundary condition) was assigned to the outer boundaries to accurately model the propagation of the magnetic field beyond the solution space. The number of turns of the excitation coil utilized in the model was selected as $N = 1000$. The B-H curve employed in the analyses was defined by the numerical data corresponding to the graph presented in Fig. 2(c) in the previous section.

The geometry of the MFL system designed in the 3D FEM simulation environment is shown in Fig. 4.

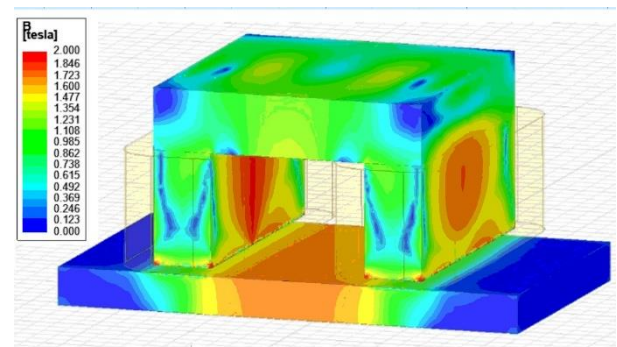


Fig. 4. 3D FEM geometry of the designed MFL system.

The analysis process was repeated for 5 different magnetomotive force levels. The varying Ni values applied to the system were obtained by adjusting the coil current while

maintaining a constant number of coil turns. Considering the principle of generating a near-saturation flux density within the test material, Ni values producing flux densities in the range of 1.7 T to 1.9 T were selected for these analyses. Consequently, the magnetic flux densities generated by the system in the test material were acquired for 5 different Ni levels. Using the acquired data as a reference, the results obtained from the MEC and SMEC models were evaluated. The utilization of this approach is imperative due to the impossibility of directly measuring the magnetic flux density within a solid material in physical experimental setups. Furthermore, the magnetic sensors employed in real-world systems possess limited measurement capacity and spatial resolution.

III. PROPOSED SMEC MODEL

In standard MEC models, accurately modeling non-homogeneous flux distributions is challenging due to physical constraints, and this limitation can lead to erroneous results. In MFL testing systems, where high flux densities must be achieved, these error rates become more pronounced. Furthermore, the effects of flux density-related errors on the detected defect signal are non-linear. Therefore, the success of the defect characterization process performed over the detected defect signal profile requires high-accuracy flux density data. To achieve the targeted accuracy rates, the conventional MEC model must be improved. It is observed that advanced MEC models in the literature are mostly based on segmentation procedures applied to the length of the material, and a sufficient number of segmentations are made to reduce errors to negligible levels. This approach is parallel to the Finite Element Method (FEM), which represents the actual physical structure more precisely.

Fig. 5 shows the magnetic flux density distribution map obtained from the 3D FEM analysis.

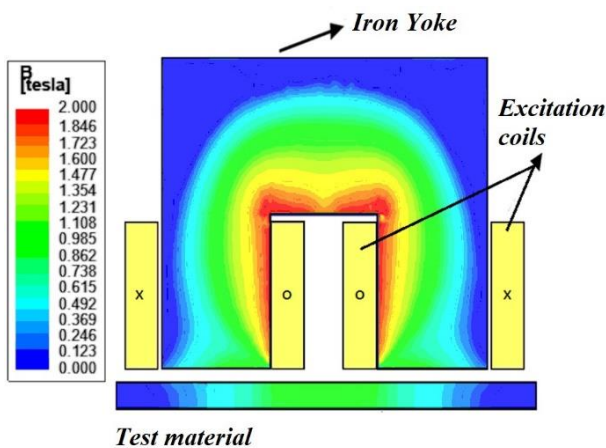


Fig. 5. Magnetic flux density distribution of magnetic materials in an MFL system.

In the Fig. 5, the non-homogeneous effects in the flux density distribution can be clearly seen. Due to the coils generating opposite magnetic poles, the flux densities exhibit an increasing variation as they approach the regions close to the inner channel of the yoke. This effect is observed along both the length and the cross-section of the U-type yoke. In this study, to account for the variations in these critical regions, segmentation was applied to the cross-section of the leg as well as the length of the winding leg. In the MEC model, three distinct regions were defined for

the winding leg length as 'lower', 'middle', and 'upper'; and three distinct regions for the winding cross-section as 'inner', 'middle', and 'outer'. The SMEC model constructed in this way is presented in Fig. 6.

In the SMEC model, magnetic paths are defined in the form of magnetic permeance (P). For an accurate circuit analysis, the total magnetomotive force provided by the excitation inductors was proportionally distributed to the segments in the corresponding branches of the system.

In addition to the useful fluxes in the magnetic system, undesirable leakage fluxes that complete their circuits through the air medium also occur. The distribution of these leakage fluxes can be observed in Fig. 2(b) presented in the previous section. Leakage fluxes reach their highest levels particularly in the yoke's slot, where there is a narrow air gap. This is due to the fact that the opposite magnetic poles at the coil legs create a highly potent and intense field of attraction within the slot. An increase in the channel distance reduces the flux density within the test material. In this scenario, a significantly higher magnetomotive force is required to restore the flux density to its previous level. Intra-channel leakage fluxes form an energy profile in this region that is of very high density and increases as it approaches the opposite poles. To reflect the rapid changes occurring within the slot, slot leakage fluxes are defined as reluctance rather than constant ones. In the SMEC model, the energy and flux variation in this region is modeled as two separate permeance elements, namely P_{hl1} and P_{hl2} .

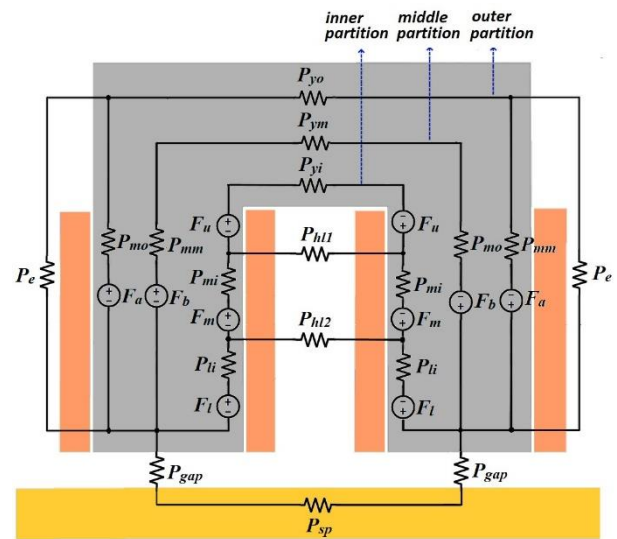


Fig. 6. Proposed SMEC structure.

Another leakage fluxes that must not be neglected is the one that completes its circuit through the external air medium between the outer sections of the bridge arms. Since its density is relatively low compared to the inner channel, this path is represented in the model by a constant permeance, P_e . These leakage fluxes primarily affect measurement accuracy compared to leakage fluxes in distant regions of the MFL system.

A MEC Model Analysis

The analysis of MEC models can be performed using mesh current or nodal voltage methods derived from fundamental circuit theory. In the literature, the mesh current method is more frequently preferred for the analysis of magnetic fluxes [30]. In this study, the MEC model analysis of the MFL system was

carried out with the aid of an iterative convergence algorithm [20]. The algorithm executes a series of iterative processes to solve matrix-form circuit equations composed of non-linear and constant permeance components. This iteration process is terminated when the error value in each loop falls below 0.001 T. Upon completion of the algorithm, the magnetic flux densities and field intensities for all points in the circuit are calculated using the obtained loop currents. The equations necessary to calculate these magnetic permeabilities are given in the appendix to the article.

IV. RESULTS

The 3D FEM analyses were conducted by determining five distinct magnetomotive force (N_i) values, aimed at generating target magnetic flux densities ranging from 1.7 T to 1.9 T within the test specimen. These selected N_i values served as input parameters for both the conventional MEC and the proposed SMEC analyses, and the resulting magnetic flux densities within the material were computed via an optimization algorithm. The magnetic flux densities derived from the developed analytical models were subsequently benchmarked against the 3D FEM reference results. The acquired data, alongside the respective accuracy metrics of each model, are presented in Table II. The variation of the induced magnetic flux density in the test material as a function of the applied magnetic excitation (magnetomotive force) is graphically depicted in Fig. 7.

Table II. Flux density values and accuracy rates obtained for the MEC and SMEC models.

N_i	FEM	MEC	SMEC	MEC Accuracy (%)	SMEC Accuracy (%)
2800	1.697	1.838	1.733	91.69	98.04
3000	1.752	1.977	1.787	87.16	98.23
3200	1.805	2.053	1.848	86.26	97.91
3400	1.851	2.081	1.886	87.57	98.32
3600	1.889	2.098	1.915	88.94	98.76
Average				87.41	98.26

The comparative outcomes demonstrate that the proposed SMEC model, which incorporates length and cross-sectional segmentation, yields results significantly closer to the reference data, providing an approximate 11% enhancement in accuracy compared to the traditional equivalent circuit model.

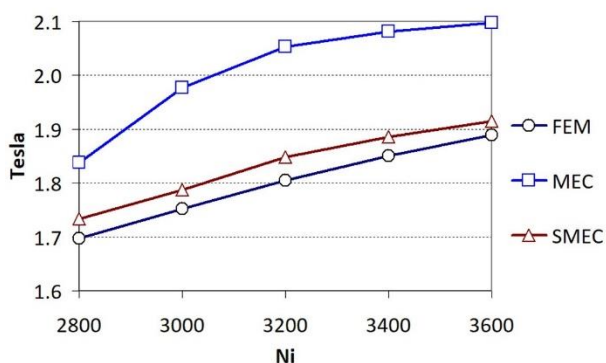


Fig. 7. The variation of flux density in the test material with respect to the applied magnetomotor force.

The computational analyses for both the MEC and FEM frameworks were executed on a workstation equipped with a 2.9

GHz Intel Core i9-12900H processor, 32 GB of RAM, and a 64-bit Windows 11 operating system. While the average computation time for the FEM simulations was 21.5 minutes, this duration was drastically reduced to 5.2 seconds for the MEC model analyses. Furthermore, it was observed that during sequential FEM runs, the repetitive processes of parameter modification, system setup, and simulation initialization introduced significant additional time overheads.

V. CONCLUSION AND RECOMMENDATIONS

The physical implementation phase of magnetic system design often presents challenges that mandate extensive iterative testing. The need to accommodate varying material dimensions and diverse compositions throughout the design cycle necessitates repetitive computational analyses. In this regard, Magnetic Equivalent Circuit (MEC)-based modeling frameworks provide a highly robust and efficient alternative for industrial processes where rapid prototyping is essential.

In this study, the performances of the conventional MEC and the developed SMEC models were comparatively investigated, utilizing 3D FEM analysis results as a benchmark. The findings establish that the SMEC model serves as a highly effective and reliable tool for magnetic system analysis. This is attributed to the fact that the proposed SMEC model is based on cross-sectional segmentation, thereby reflecting the effects of inhomogeneous flux distribution within the material cross-section onto the equivalent circuit with exceptional precision. This advantage becomes particularly pronounced in applications utilizing high flux densities and thick-walled materials, such as Magnetic Flux Leakage (MFL) testing systems. Furthermore, by increasing the segment density in the SMEC model depending on the requirements of specific applications, higher levels of accuracy can be achieved. Thus, high-fidelity magnetic analyses can be performed by establishing an optimal balance between computational cost and analytical precision.

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APPENDIX

$$P_{li} = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{w_w - (d_h + d_{h2})} \quad (A1)$$

$$P_{mi} = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{(d_h - d_{h1}) + d_{h2}} \quad (A2)$$

$$P_{yi} = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{w_s + w_i} \quad (A3)$$

$$P_{mm} = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{\left(w_w + \frac{w_e}{2} \right) + d_{h2}} \quad (A4)$$

$$P_m = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{w_s + w_i} \quad (A5)$$

$$P_{yo} = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{w_w + \left(4 * \frac{w_e}{3} \right)} \quad (A6)$$

$$P_{yo} = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{w_w + \left(4 * \frac{w_e}{3} \right)} \quad (A7)$$

$$P_{mo} = \frac{l_c \left(\frac{w_e}{3} \right) \mu_B(.)}{w_w + \left(2 * \frac{w_e}{3} \right)} \quad (A8)$$

$$P_{sp} = \frac{l_c \left(\frac{w_m}{3} \right) \mu_B(.)}{w_s + w_e} \quad (A9)$$

$$P_{gap} = \frac{\mu_0 l_c (w_e/3)}{l_g} \quad (A10)$$

$$P_{e1} = \frac{\mu_0 (w_e/3) l}{d_w + \sqrt{(w_e/3)^2 + 2w_w \cdot (w_e/3)}} \quad (A11)$$

$$P_{e2} = \frac{\mu_0 l}{256w_w^2 d_w^2} \left[k_2^4 + \sqrt{2} k_1 k_2^3 + \frac{1}{4} k_1^2 k_2^2 - \frac{\sqrt{2}}{8} k_1^3 k_2 + \frac{\mu_0 l}{256w_w^2 d_w^2} \right] \quad (A12)$$

$$k_1 = |w_w - 2d_w| \quad k_2 = \frac{1}{\sqrt{2}} \min(w_w, 2d_w)$$

$$P_e = P_{e1} + P_{e2} \quad (A13)$$

BIOGRAPHY



Hasan Hüseyin Çelik received the B.S. and M.S. degrees in electronics and communication engineering from Yildiz Technical University (YTÜ) in 1987 and 1991, respectively. He received the Ph.D. degree in electronics and computer education from Marmara University, Istanbul, in 1999. He currently serves as an

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