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Montreal, QC, Canada, June 29-July 2, 2015

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Compumag 2015 Chairman's Foreword

FROM June 29 to July 2, 2015, McGill University in Montreal, Canada, was the host of the 20th edition of the International Conference on the Computation of Electromagnetic Fields (Compumag 2015). Every two years since its inception in Oxford, U.K., in 1976, Compumag has provided a forum for the international computational electromagnetics community to come together and exchange ideas and develop new research areas. Over its history, we have seen the computation of electromagnetic fields advance from extremely simple systems in the early days of finite elements and integral methods to the advanced systems of today capable of dealing with 3-D systems handling eddy currents, nonlinearity, and motion on a laptop computer. Simulation has clearly come of age in our area.

For Compumag Montreal, researchers from around the world were invited to submit leading edge work on the numerical computation of electromagnetic fields in areas ranging from mathematical modeling and formulations through optimization and design to novel computational methods for machines and devices. The Editorial Board, run by Prof. Jan Sykulski of Southampton University, U.K., and consisting of 232 reviewers, selected the papers for presentation at the conference through a rigorous process involving multiple reviewers for each paper. The accepted papers came from 32 countries and were spread across the 16 major topics of the conference. The largest contributor was the People's Republic of China with 63 papers, followed closely by Japan with 55 and South Korea with 49. France was the leading European contributor with 44 papers. An effort was made in the Call for Papers for Compumag to try to focus the submissions on novel techniques and to limit the applications to demonstrations of novel methodologies, and more emphasis was placed on optimization and design, with this becoming the largest category with 91 papers accepted. As always, static and quasi-static fields and numerical techniques came in the top 3, with 71 and 61 papers, respectively. However, emphasis is clearly shifting in some areas, with material modeling being the fourth largest category with 35 papers. These numbers show the recent evolution of the field of computational electromagnetics toward the more practical issues encountered in the design of real devices.

The conference was attended by 410 delegates from 29 countries, and papers were presented in 24 poster and 8 oral sessions. Hosting the conference on campus, rather than in a hotel, had the effect of keeping delegates together and encouraging discussions, resulting in many new research partnerships being developed during the conference. One of the highlights of the conference is the awarding of the Rita Trowbridge award to the best paper authored and presented by a young researcher registered as a student. The winning paper was chosen by a committee headed by Prof. Herbert de Gersem of Darmstadt University, Germany. He and his team did a terrific job, and the award finally went to Konstantin Weise from TU Ilmenau, Germany. Commendations were given to Korinna Brackebusch from University of Rostock, Germany; Peter Gangl from Johannes Kepler University, Linz, Austria; and Yuki Sato from Hokkaido University, Japan.

Over 400 papers were presented at the conference, and each author of a presented paper was invited to submit an extended version of the paper for consideration for publication in the IEEE TRANSACTIONS ON MAGNETICS. The statistics are presented in the preface from the Editor-in-Chief. We hope that you find the finally accepted papers stimulating and thought-provoking and that they will direct and form the basis of the work that will be developed for the next Compumag conference.

The conference was organized by the professors and students of the Computational Electromagnetics Laboratory in the Department of Electrical and Computer Engineering of McGill University together with FPI Events. Many thanks are due to all the volunteers, reviewers, and organizations, especially Lucy Felicissimo and June Viau from FPI Events, who made this conference the success it was. Without all the help, it could not have happened. On behalf of the International Compumag Society and Compumag Montreal, we would like to thank all the participants, without whom there would not have been a conference. We hope you enjoyed the Montreal experience and look forward to meeting everyone again in Korea in 2017.

DAVID A. LOWTHER, *General Chair*
Compumag 2015

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Preface From the Editor-in-Chief

IT IS my great pleasure to present to you this special issue of the IEEE TRANSACTIONS ON MAGNETICS containing selected extended papers originally presented at the 20th Conference on the Computation of Electromagnetic Fields (Compumag 2015), which took place in Montreal from June 28 to July 2, 2015. From the original nearly 650 papers submitted to Compumag Montreal, 423 were presented at the conference and 348 submitted in extended format to the IEEE TRANSACTIONS ON MAGNETICS. Of those, 231 have been accepted and are included in this issue.

I would like to thank all Editors and Reviewers for their hard work and for meeting the deadlines. In most cases there has been enough time for a round or two of revisions, I am confident, therefore, that the published papers have achieved high standard in terms of both technical content and the quality of presentation. Thanks are also due to the staff of the IEEE TRANSACTIONS ON MAGNETICS for their support in preparing this issue. But most of all, many thanks to all the authors for preparing the manuscripts carefully and for responding to the comments and suggestions of the reviewers.

I look forward to the next Compumag conference in Korea in 2017.

JAN K. SYKULSKI, *Editor-in-Chief*
Compumag 2015

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A. Pierquin, S. Brisset, and T. Henneron

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A. A. Arkadan and M. El Hariri

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S. Mezani, T. Hamiti, L. Belguerras, T. Lubin, and C. Gerada

8102304 **On the Role of Robustness in Multi-Objective Robust Optimization: Application to an IPM Motor Design Problem**
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R. Silva, A. Salimi, M. Li, A. R. R. Freitas, F. G. Guimarães, and D. A. Lowther

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J.-Y. Song, J. H. Lee, Y.-J. Kim, and S.-Y. Jung

8200404 **Mass Ionized Particle Optimization Algorithm Applied to Optimal FEA-Based Design of Electric Machine**
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8200504 **Design of Saliency-Based Sensorless-Controlled IPMSM With Concentrated Winding for EV Traction**
M.-S. Lim, S.-H. Chai, and J.-P. Hong

8200606 **Search Region Management Method for Local Search Algorithm Employing Design Optimization of Brushless DC Motor**
T.-Y. Lee, P. X. Trung, J.-W. Kim, Y.-J. Kim, and S.-Y. Jung

8200704 **Design and Optimization of Electric Continuous Variable Transmission System for Wind Power Generation**
Y. Wang, S. Niu, W. N. Fu, and S. L. Ho

8200804 **A Computationally Efficient Algorithm for Rotor Design Optimization of Synchronous Reluctance Machines**
M. H. Mohammadi, T. Rahman, R. Silva, M. Li, and D. A. Lowther

8200904 **Characteristics Analysis of a 2-D Differentially Coupled Magnetic Actuator**
Y. Sakaidani, K. Hirata, and N. Niguchi

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8201104 **Analytical Calculation of the Magnetic Vector Potential of an Axisymmetric Solenoid in the Presence of Iron Parts**
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8201204 **Optimal Design of an Axial Flux Permanent Magnet Synchronous Motor for the Electric Bicycle**
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8201304 **A Novel Multimodal Optimization Algorithm for the Design of Electromagnetic Machines**
C.-H. Yoo, D.-K. Lim, and H.-K. Jung

8201404 **Effects of Stress and Magnetostriction on Loss and Vibration Characteristics of Motor**
H. Ebrahimi, Y. Gao, H. Dozono, K. Muramatsu, T. Okitsu, and D. Matsuhashi

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8400104 **Compensation Considerations for Bidirectional Inductive Charging Systems of Electric Vehicles With Coil Positioning Flexibility**
S. G. Cimen, A. Pfannkuchen, and B. Schmuelling

8400204 **Transformer Windings' *RLC* Parameters Calculation and Lightning Impulse Voltage Distribution Simulation**
T. Župan, B. Trkulja, R. Obrist, T. Franz, B. Cranganu-Cretu, and J. Smajic

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9100104 **Electroquasistatic-Thermal Modeling and Simulation of Station Class Surge Arresters**
Y. Späck-Leigsnering, E. Gjonaj, H. De Gersem, T. Weiland, M. Gießel, and V. Hinrichsen

9100204 **Error Field Impact on Plasma Boundary in ITER Scenarios**
L. Barbato, A. Formisano, R. Martone, and F. Villone

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9400304 **An Improved Multi-Objective Genetic Algorithm for Large Planar Array Thinning**
Y.-F. Cheng, W. Shao, S.-J. Zhang, and Y.-P. Li

9400404 **Electromagnetic Interference Prediction of ±800 kV UHVDC Converter Station**
H. Sun, X. Cui, and L. Du

9400504 **Calculation of Electromagnetic Radiation of VSC-HVdc Converter System**
H. Sun, L. Du, and G. Liang

9400604 **Adaptive Strategies in the Leader Propagation Model for Lightning Shielding Failure Evaluation: Implementation and Applications**
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Fast Magnetic Flux Line Allocation Algorithm for Interactive Visualization Using Magnetic Flux Line Existence Probability

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The visualization of magnetic flux lines is one of the most effective ways to intuitively grasp a magnetic field. The depiction of continuous and smooth magnetic flux lines according to the magnetic field is of paramount importance. Thus, it is important to adequately allocate the distribution of magnetic flux lines in the analyzed space. We have already proposed two methods of determining the allocation of magnetic flux lines in 3-D space. However, both the methods exhibited a long computation time to determine the allocation of magnetic flux lines. For solving this problem, in this paper, we propose a new improved method for the correct allocation of magnetic flux lines in the 3-D space with modest computational cost. The main advantages of this method are shorter computation time, correct allocation of the magnetic flux lines, and, especially, short computation time for the visualization of magnetic flux lines when changes in the number of depicted flux lines are requested.

***Index Terms*—Magnetic field, magnetic flux line, probability distribution, visualization.**

I. INTRODUCTION

SIGNIFICANT improvements in the computer technology enabled large-scale electromagnetic simulations, which usually, as a result, generate huge amount of numerical data. Hence, it is difficult to grasp a magnetic-field or electric-field phenomenon only from the numerically obtained results. Thus, the importance of visualizing the simulation results is increasing. The visualization of magnetic flux lines is an effective way of intuitively understanding the magnetic-field distribution in a whole 3-D space on a 2-D display, because it enables us to observe or image the strength, orientation, and locus of magnetic field simultaneously.

Magnetic flux lines have to be depicted according to the following rules.

1) The density of magnetic flux lines enables us to perceive the strength of the magnetic field $|\boldsymbol{B}|$ (T).
2) The tangential direction of the magnetic flux lines enables us to grasp the orientation of the magnetic field.

Several methods of analytically obtaining continuous and smooth magnetic flux lines from the 3-D edge finite-element analysis (FEA) results were proposed in [1]–[4]. These methods provide the visualization of magnetic flux lines satisfying rule 2). However, they mostly failed to provide a way of selection and visualization of magnetic flux line allocation according to rule 1).

Consequently, two other methods [5], [6] for magnetic flux line allocation using the bubble system [7]–[9], which provide the allocation of magnetic flux lines that satisfies rule 1) were proposed. However, the major drawback of these methods was their extremely long computation time to simulate the bubbles' movement. In some cases, it takes several hours.

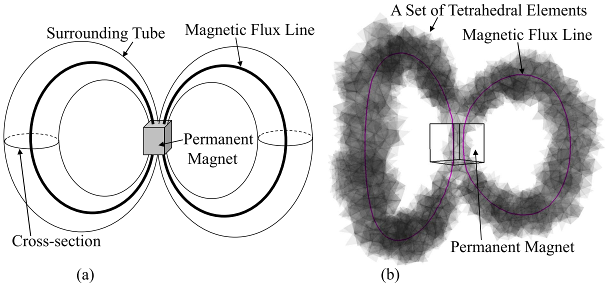

Fig. 1. (a) Visualization of magnetic flux lines based on virtual tubes [6]. (b) Magnetic flux lines surrounded by a set of tetrahedral elements in 3-D space.

In this paper, we propose a new method for the proper allocation of the magnetic flux lines based on the computation of the magnetic flux line existence (MFLE) probability. The proposed method significantly shortens the computation time in comparison with the previously proposed methods [5], [6]. Once the MFLE probability is calculated for each finite element, it can be reused for any further visualization needs. This enables us to decrease the computation time for any further visualization of the magnetic flux lines, regardless of the line density or the number of depicted flux lines in the 3-D space. Thus, the proposed method becomes highly suitable for any interactive visualization system.

II. METHOD OF MAGNETIC FLUX LINE ALLOCATION

A. Concept of the Proposed Method

In the previously proposed method [6], a magnetic flux line was surrounded by a virtual tube whose cross-sectional radius was a function of the magnitude of magnetic flux density, as shown in Fig. 1(a). The computation of these virtual tubes was based on the bubble system. However, the process of simulation of the tube's movement always took a long computation time.

With the proposed method, to shorten the computation time, we propose a new method for adequately allocating magnetic

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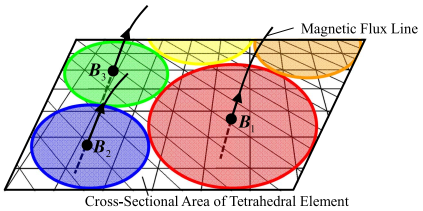

Fig. 2. One magnetic flux line penetrates one circle, whose area is inversely proportional to B_c ($c = 1$, 2, and 3). The total value of $B_c S_c$ inside of each circle has to be 1.

flux lines within the analyzed domain. Instead of virtual tubes with rounded cross sections, a set of elements that are not intersected by any other flux line is constructed around a magnetic flux line to be depicted. To decide the size of a set of tetrahedral elements in accordance with the magnitude of the magnetic flux density, we introduce a new calculation parameter called MFLE probability. Hence, since it is easy to calculate the MFLE probability, the appropriate allocation of magnetic flux lines could be obtained much quicker than the previous methods [5], [6]. Fig. 1(b) shows a set of tetrahedral elements surrounding an arbitrary magnetic flux line in the 3-D analysis domain.

B. MFLE Probability Calculation

The expected number of magnetic flux lines N_{flux} passing through a plane S is defined as

$$N_{\text{flux}} = BS \tag{1}$$

where B and S are the magnitudes of the magnetic flux density perpendicular to the plane and the area of the plane, respectively. As shown in Fig. 2, a magnetic flux line penetrates into a circle that corresponds to the cross section of a virtual tube [6]. The total product $B_c S_c$ inside one circle c has to be 1

$$\int_c B_c dS = 1. \tag{2}$$

In the proposed method, to simplify the computation, a set of elements instead of a virtual tube is used. Hence, the number of magnetic flux lines N^i_{flux} passing through one tetrahedral element i could be calculated as follows:

$$N^i_{\text{flux}} = B_i S_i \tag{3}$$

where B_i and S_i are the magnitudes of the magnetic flux density and the area of a cutting plane of the element i, respectively. Similar to (2), the sum of N^i_{flux} of the elements has to be 1

$$\sum_i N^i_{\text{flux}} = 1. \tag{4}$$

For visualization purposes, when the magnetic flux density is too high (or too low), a user cannot effectively grasp the magnetic field phenomenon only by means of depiction of the magnetic flux lines in accordance with (4). Hence, in the proposed method, an additional parameter β ($\beta > 0$) is introduced in order to adjust the number of depicted magnetic flux lines in correlation with the magnetic flux density. Using the parameter β, (4) could be rewritten as follows:

$$\alpha_i = \beta B_i S_i, \quad \sum_i \alpha_i = \sum_i \beta B_i S_i = 1 \tag{5}$$

where α_i is the parameter called the MFLE probability of the element i. When one magnetic flux line is depicted in a region with a total MFLE probability of 1, the allocation of magnetic flux lines fully satisfies rule 1). Fig. 3 shows a set of elements with a total MFLE probability of 1, distinguished by different colors. Since this new set of elements is not a tube but a polygon, it is easier to compute (5), which results in very short computation time that exhibits our newly proposed calculation method.

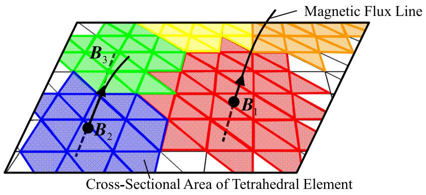

Fig. 3. Set of elements with a total MFLE probability of 1 is distinguished by different colors.

C. Calculation Procedure

As preprocessing, the magnetic flux density $\boldsymbol{B}$ and the cross-sectional area S of every tetrahedral element are computed, followed by the calculation of the MFLE probability α for each element in accordance with (5). S is perpendicular to $\boldsymbol{B}$, and passes the gravity point of each tetrahedral element. Next, the procedure continues as follows.

Step 1: Select element i with the largest value of $B_i \alpha_i$.

Step 2: Compute a magnetic flux line placed at the gravity point of the selected element i. The magnetic flux line is analytically computed using FEA results [1], [2]. The elements through which this magnetic flux line passes are defined as e_j ($j = 1, 2, \ldots, N_{\text{p}}$), where N_{p} is the total number of elements passed through by this magnetic flux line.

Step 3: Update the MFLE probability $\alpha_{e_j,\text{new}}$ of element e_j as

$$\alpha_{e_j,\text{new}} = \alpha_{e_j,\text{old}} - \min(\alpha_{e_j,\text{old}}, 1.0). \tag{6}$$

Step 4: Calculate the MFLE probability γ_{k+1} ($\gamma_1 = 1.0$) as

$$\gamma_{k+1} = \gamma_k - \sum_{\lambda \in \boldsymbol{D}_k} \min(\alpha_{\lambda,\text{old}}, \gamma_k / n_k) \tag{7}$$

$$\text{with } n_k = |\boldsymbol{D} \Delta \boldsymbol{a}| \tag{8}$$

where k is the number of steps of the MFLE probability decreasing process, $\boldsymbol{D}$ is the element that has already updated the MFLE probability in Step 3 or 5, and $\boldsymbol{a}$ is the adjacent element of $\boldsymbol{D}_{k-1}$. When γ_{k+1} is equal to 0.0 and j is smaller than N_{p}, increase j by 1 and return to Step 3. When γ_{k+1} is equal to 0.0 and j is equal to N_{p}, go to Step 6.

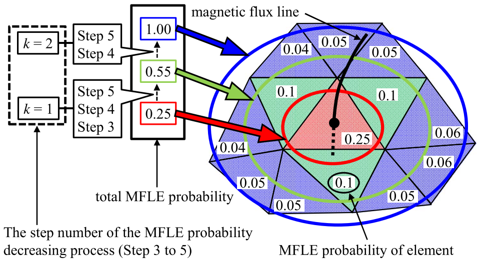

Fig. 4. Visual representation of MFLE probability decreasing process (from Step 3 to Step 5). At Step 3, the MFLE probability of a red element (e_j) penetrated by a magnetic flux line decreases to 0. At Step 4, $\gamma = 1.0 - 0.25 = 0.75$, and then in Step 5, the MFLE probability of the green elements is updated. Subsequently, the processes in Steps 4 and 5 are repeated until $\gamma = 0$ (the blue-colored elements).

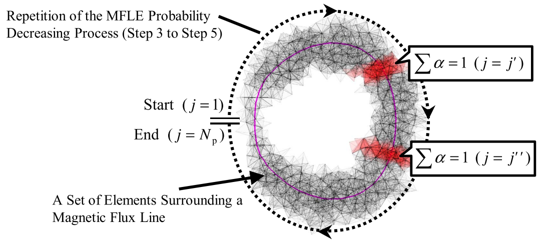

Fig. 5. Conceptual explanation of a process of allocation of a magnetic flux until it is surrounded by all elements.

Step 5: Update the MFLE probability $\alpha_{\mathrm{ADJ}_l,\mathrm{new}}$ of the adjacent elements $\mathrm{ADJ}_l (\in D\Delta a)$ as

$$\alpha_{\mathrm{ADJ}_l,\mathrm{new}} = \alpha_{\mathrm{ADJ}_l,\mathrm{old}} - \min(\alpha_{\mathrm{ADJ}_l,\mathrm{old}}, \gamma_{k+1}/n_{k+1}). \tag{9}$$

Increase l by 1 and repeat Step 5 before l exceeds n_k, and then increase k by 1 and return to Step 4.

Step 6: When at least one element has larger MFLE probability than the arbitrary threshold ε, return to Step 1. Otherwise, all the magnetic flux lines computed in Step 2 are depicted.

Fig. 4 shows the conceptual explanation how the MFLE probability decreases to 0 from Step 3 to Step 5. As shown in Fig. 5, the processes in Steps 3–5 are repeated for each magnetic flux line until j reaches N_p. Consequently, each magnetic flux line is surrounded by the elements not penetrated by any other magnetic flux line [see Fig. 1(b)]. After finishing all allocation processes, the following relation is satisfied:

$$\sum_i \sum_j \alpha_{ij} = \alpha_{\mathrm{all}} \tag{10}$$

where α_{ij} and α_{all} are the MFLE probabilities of the element j passed through by the magnetic flux line i and a total MFLE probability of all the elements in the whole analysis domain, respectively. Since (10) is satisfied, the allocation of all magnetic flux lines obtained by the proposed method is appropriately determined according to rule 1).

D. Changing the Number of Magnetic Flux Lines

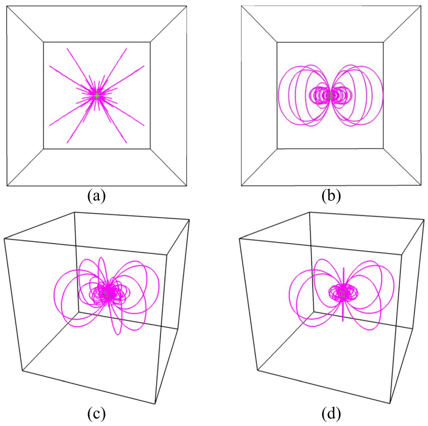

Fig. 6. Visualization of 80 magnetic flux lines for the model of single permanent magnet model. (a)–(c) Eighty lines visualized from different viewpoints—initial drawing. (d) Fifty six lines visualized when changing the number of lines for the second drawing.

One function usually requested in any interactive visualization system is its ability to arbitrarily change the number of visualized magnetic flux lines. The previous method [6] exhibited the same long time when changing the number of magnetic flux lines, as when the initial calculation of the magnetic flux lines; therefore, it was not suitable for interactive visualization.

In the proposed method, redrawing of different numbers of magnetic flux lines takes only a few seconds, after their initial adequate allocation. Actually, when changing the number of the flux lines to be visualized, only the parameter β in (5) has to be accordingly reset. However, since $B_i S_i$ for all of the elements has already been calculated during the initial drawing, for redrawing different numbers of flux lines, the system needs only a very short computation time spent to recalculate the MFLE probability α_i based on the previously obtained $B_i S_i$. In this method, the calculation of $B_i S_i$ takes ~96% of the total computation cost.

III. APPLICATIONS

In order to confirm the validity of the proposed method, we present its application to two models: 1) a simple single permanent magnet model and 2) a motor model. Using these two models, the following features of the proposed method are shown: 1) the adequate allocation of the magnetic flux lines; 2) the short computation time; 3) easy method for changing the number of flux lines; and 4) applicability of the method for magnetic flux lines visualization for more complex models.

A. Simple Model Consisting of Single Permanent Magnet

1) Adequate Allocation of the Magnetic Flux Lines: Fig. 6 shows the visualization of 80 magnetic flux lines allocated by the proposed method, and visualized in accordance with the method presented in [1]. Fig. 7 shows the process of changes of the MFLE probability α distribution in the cross section of the permanent magnet until the allocation of all magnetic flux lines is determined. Comparison between the flux lines presented in Fig. 6 confirms that the proposed method provides the adequate allocation of magnetic flux lines, fully satisfying rule 1).

2) Decreasing of the Computation Time: Table I shows the number of drawn magnetic flux lines and elements. Fig. 8 shows the computation time for the first and the second

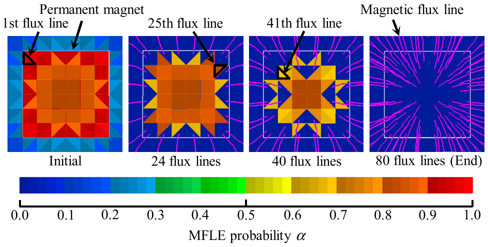

Fig. 7. Change in MLFE probability α distribution on the cross section of permanent magnet until the allocation of all magnetic flux lines is determined by the proposed method, when the 1st, 25th, 41st, and whole 80 magnetic flux lines (from left to right) are computed. After visualizing the whole 80 magnetic flux lines, the MLFE probability α is 0 everywhere (blue elements everywhere).

TABLE I
NUMBER OF MAGNETIC FLUX LINES AND ELEMENTS

Method	Old Method [6]	Proposed Method
# of elements	79507	384000
# of magnetic flux lines	50	80

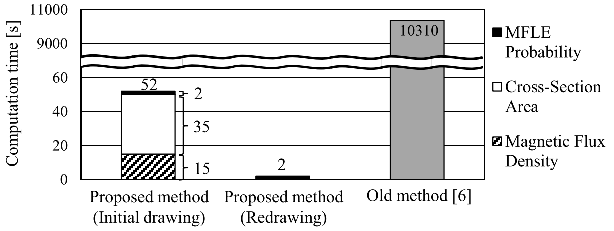

Fig. 8. Comparison of computation time in the old and the proposed method. In the proposed method, breakdown of computation time is shown.

drawing in the old method and the newly proposed method, respectively. However, only the first drawing computation time of the old method is shown, and almost the same computation time is wasted for the second drawing.

3) Decreasing the Computation Time During Redrawing: Fig. 8 also shows the breakdown of the total computation time of the proposed method and for each process separately. Since during the redrawing process, some lengthily processes are omitted, i.e., the computation of the magnetic field $\boldsymbol{B}_i$ and the cross-sectional area S_i are omitted, since this calculation has already been done during the initial visualization process, during redrawing decreasing of the total computational time is significant. Consequently, these facts allow the users interactive adjustment of the number of magnetic flux lines to be visualized. As shown in Fig. 8, the computation time of the proposed method decreased from 52 s for the first drawing, down to only 2 s for the next drawing.

B. Motor Model

Next, we applied it for the visualization of the magnetic flux lines for a more complex model of an SPM motor [10]. Fig. 9 shows the visualization result of this model. In general, it is more difficult to visualize the magnetic flux lines due to multiple electromagnetic sources. However, as shown in Fig. 9, the proposed method provides an accurate allocation of the magnetic flux lines even for such electromagnetically complex models.

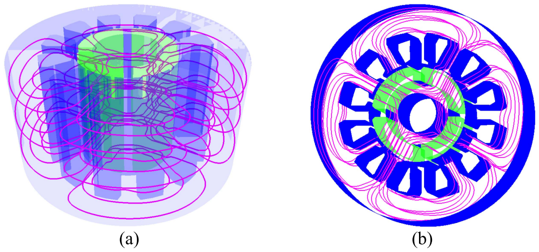
(a) (b)

Fig. 9. Visualization of magnetic flux lines allocated by the proposed method for a model of SPM motor in 3-D space. (a) Bird's eye view. (b) Top view.

IV. CONCLUSION

In order to decrease the computational cost and increase the versatility of the old visualization methods [5], [6], in this paper, we proposed a new visualization method. The proposed method computes the so-called MFLE probability, as a major parameter for the adequate allocation of the magnetic flux lines to be visualized. The major advantage of the proposed method is its short computation time, especially for redrawing various numbers of flux lines in the analysis region, which enables this method to be used for any interactive visualization systems.

In order to verify the effectiveness of the proposed method, two models with their results were presented. From these results, one can easily confirm that the allocation of the magnetic flux lines obtained by the proposed method satisfies rule 1), the computation time is much shorter than the old methods, and the application for magnetic flux visualization of a complex electromagnetic device is easily attainable.

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Aims & Scope

Science and technology related to the basic physics and engineering of magnetism, magnetic materials, applied magnetics, magnetic devices, and magnetic data storage. The *IEEE Transactions on Magnetics* publishes scholarly articles of archival value as well as tutorial expositions and critical reviews of classical subjects and topics of current interest.

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