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A Comparative Study of White-Box Modeling Techniques for Digital Twin Development of Traction Motors

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Executive Summary

This study compares white-box modeling techniques to evaluate their compatibility in the digital twin development of electrical traction machines. The evaluation criteria for multiphysics models are, but not limited to, computational time, accuracy, power scalability, material & thermal dependencies. To generalize different electrical machine technologies, they are investigated under the scope of double salient machines, referring to the non-uniformity of the airgap between stator and rotor. Furthermore, a framework is presented on how to extend a multiphysics model towards a fast and accurate grey-box machine model required by the machine's digital twin.

1 Introduction

In recent years, electrification in transportation has gained momentum especially in the research towards selection of next generation electrical traction machine technologies for both hybrid and battery electrical vehicles. In today's electrified powertrains, the leading machine topology has been permanent magnet synchronous machine (PMSM) thanks to its high efficiency, high power and torque density [1]. However, nowadays, due to several drawbacks of rare-earth magnet usage, such as their low recyclability percentage, the limited availability of their resources and robustness concerns due to magnet demagnetization at high temperatures, rare-earth-free machine topologies have gained the researchers' attention [2]. Some of the possible candidates for traction applications among rare-earth-free machines are switched reluctance machines (SRM) [3], [4], synchronous reluctance machines (SynRel) [5], [6] and variable-flux reluctance machines (VFRM) [7], [8] Even if all three topologies hold the advantage of robust structure and high reluctance torque production capability due to their double salient structures, they can suffer from low power factor, low torque and power density, high acoustic noise and vibration issues [9]. For these reasons, the mentioned rare-earth-free and double salient machine topologies are required to be well-characterized and optimized considering the requirements in order to determine the most optimum operating conditions for the load and the machine. To minimize the dependency of modeling approaches on machine technology and to reduce time-to-market, digital twins can be used in the pre-development phase of the machine. Traditionally, an iterative design and analysis procedure requires fast and reliable machine models to minimize the discrepancy between the design and the actual prototype, as well as to decrease the high-fidelity simulation duration. As a result, to satisfy both these conditions, a digital twin for double salient electrical machines that includes the thermal, mechanical and electromagnetic properties of the machine is a good candidate being both accurate and having low computational cost. These objectives can be achieved by combining a fast and precise white-box modeling technique and merging it with an experimental dataset.

2 Multiphysics Modeling of Traction Machines for Digital Twins

Increasing use and production of electric vehicles cause a drastic change in overall in the automotive industry as electric vehicles are completely different than traditional vehicles with combustion engines by means of both design and production. Due to this fact, the design and manufacturing processes for electric vehicles have been modified and much effort put in this research area. One of the most critical steps in this domain is the drivetrain development for electric vehicles, which requires complex analyses and simulations. Recently, leading automotive companies are solicitous about creating digital twins of vehicles to improve the design, analysis and testing procedure of the vehicles, both alone [10] and as collaborations [11], [12] These studies include both system and component level tests and analyses.

In order to successfully complete the component level studies and achieve a successful system integration, the compatibility of each component with each other should be simulated, tested and verified. For that reason, multiphysics modeling of electrical machines gain importance as such models show the machine with all aspects and with any possible interaction with the drivetrain. Such an approach is especially beneficial and critical for system-level drivetrain analyses such as obtaining efficiency maps and loss distributions, thermal management of the drivetrain, material characterization, operation optimization for different drive cycles and noise-vibration-harshness (NVH) analyses.

On top of the mentioned minor optimization and analysis problems, multiphysics modeling introduces the benefit of investigating major design decisions such as the scaling of an already present design, creating fast models for feasibility studies (for different material characteristics) and exploiting the introduction of new materials in the electrical machine design.

For these analyses, the observation of the temperature at each step is crucial. At each operation point, the changing dynamics, such as temperature, affect the machine, therefore the model performance. Hence, in a multiphysics electrical machine model, the operation points can be treated as the individual steps of the iterative calculation to be able to observe the dynamic effect of multiphysics domains on each other. Yet, as the thermal time constant of a system is larger than its electrical time constant, observing the thermal limits and characteristics of an electrical machine would require a long simulation. Because of this, it is vital that the core model of the digital twin to be fast yet meticulous. Commercial multiphysics simulation software fail in this manner and this can be achieved by enhancing a fast analytical model with a real-life experimental dataset using data hybridization techniques, in short, a grey-box model structure.

3 Grey-Box Model Structure

The term “grey-box model” stands for a mixed model topology that includes a physics-based analytical system, namely a white-box model and a data-driven black-box model [13]. In this study, the primary purpose is to form a multi-layer grey-box model to obtain a realistic electrical machine digital twin. This multi-layer structure can be analyzed for different operation conditions of different physical domains.

Figure 1 shows an illustration of the overall modeling structure. Partitioned to three physical sub-domains, which denote thermal, mechanical and electromagnetic properties of the electrical machine, each of these sub-domains are considered as different grey-box models. For the applications of the digital twin which covers mechanical steady-state operation, the mechanical sub-domain can also be left out of consideration. For the remaining cases, the mechanical sub-domain consists of the basic torque-balance equation of the rotary machines:

$$T_{em} - T_{mech} = J\ \frac{d\omega_m}{dt}$$

In this equation, T_{mech} denotes the load torque on the machine’s shaft and T_{em} shows the electromagnetic torque produced by the machine. Hence, it provides the connection between the electromagnetic and mechanical sub-domains.

For the electromagnetic sub-domain, the generic torque-speed (T-ω) characteristics curve is partitioned to four parts as low torque low speed, high torque low speed, low torque high speed and high torque high speed regions. This partitioning is made considering the boundaries due to the dominance of the magnetic saturation effect is and due to the dominance of eddy current losses because of high-speed. The base electromagnetic model is a simple and magnetically linear model; and these four regions are defined to include the magnetic saturation, eddy current loss effects to the model while building the grey-box model.

That is, different levels of fidelity models are integrated at this part to obtain the electromagnetic quantities and to contribute to grey-box model.

For the thermal part, the machine's thermal characteristics are modeled as a lumped-parameter thermal equivalent circuit (TEC) initially, and then they are combined with various temperature measurements from the various locations inside the machine. These temperature measurements are critical as they provide the information of loss characteristics of the machine under different operation conditions. Therefore, the data plays an important role in determining the electromagnetic quantities of the machine as it is directly related to the boundaries between the T-ω plane parts.

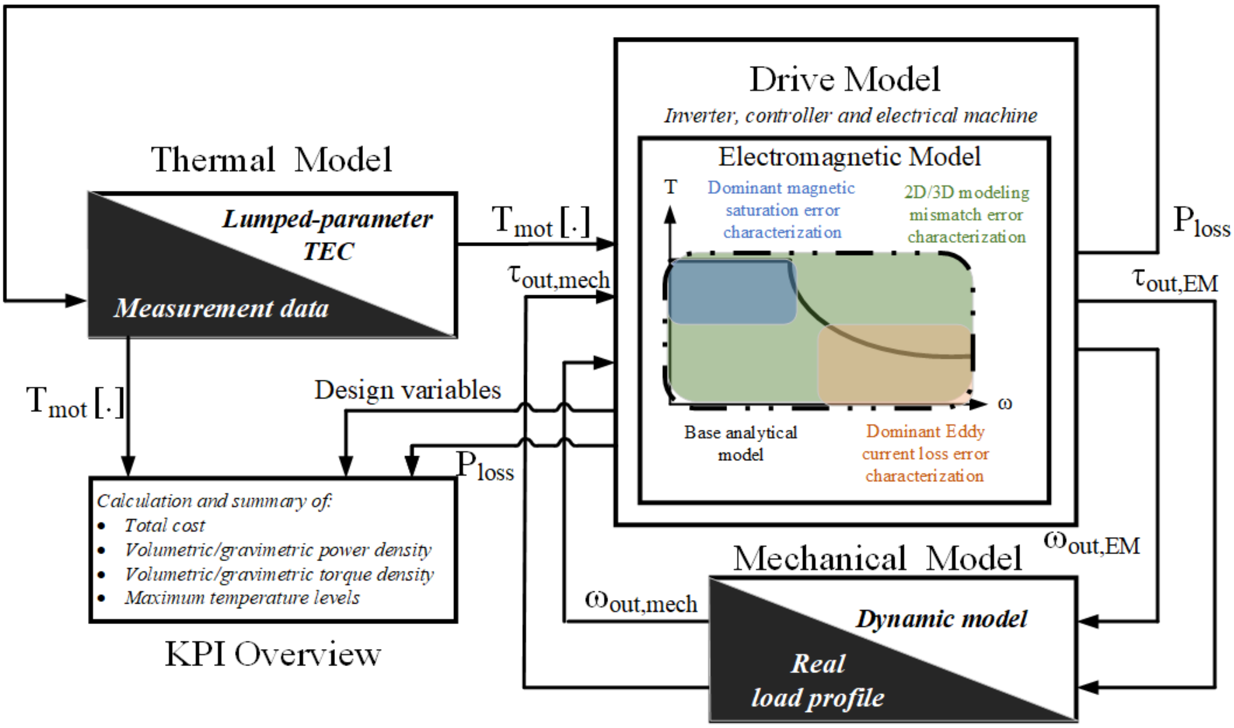


Figure 1: Main grey-box model structure and its partitioning with respect to the different operation regions

4 Electromagnetic White-Box Model Characterization

A white-box model can be defined as a model whose inner workings and whose functionality are fully known [13]. For the electromagnetic sub-domain of an electrical machine's digital twin, a white box model corresponds to an (semi-) analytical model that describes the physical relationship between the electromagnetic quantities. For most of the cases, the critical electromagnetic quantity that is being calculated is airgap magnetic flux density. Therefore, throughout this study, the term "white-box model" is often used as the analytical techniques that calculate the airgap magnetic flux density.

Modeling methods of the airgap magnetic flux density can be discussed under mainly three groups: Mapping-based methods, harmonic method and surface current/charge models. These methods differ from each other by means of several aspects. Some of these aspects are obtaining solutions for single and multi-domain systems, approximating or directly modeling the effect of slotting, accurate estimation of both radial and tangential components of the airgap magnetic flux density, convergence rate, and computational efficiency [14], [15]. All these modeling methods is compared to find the most suitable approach for multiphysics domain integration (with TEC model), and easier parameter tuning with experimental data using least squares regression method (LSR), which is the most intuitive data hybridization and error characterization method.

4.1 Comparison Criteria for the Modeling Techniques

While comparing the analytical magnetic domain modeling techniques, several criteria have to be taken into account to evaluate the suitability of a certain modeling technique for an electrical machine model. These criteria can be investigated in two categories: Model development and model operation.

4.1.1 Comparison on Model Development

The important criteria to compare the modeling types that affect the development process of the model itself are the flexibility of the model for different machine topologies, power scalable capability of the developed model output and the effort to build the model (model complexity). The importance of flexibility is the capability to adapt the model to different topologies with minimum effort. This aspect is an asset for the use of the model while making important design decisions.

Similar to the flexibility, the convenience of the model for power scalability also serves to the design steps. To be able to build a new design on top of an already built one shortens the design procedure and increases the overall efficiency for the R&D processes. Also because of the same concern, the modeling technique should not be a complex one.

4.1.2 Comparison of Model Operation

Similar to all modeling and simulation methods, in this study, the most important aspects of the model operation are the accuracy and computation time of it. As mentioned before, these kinds of multiphysics simulations are expected to take long because of the large number of iteration steps to be able to observe the dynamic effect of multiphysics domains on each other.

Furthermore, due to the multiphysics structure of the digital twin, the electrical, magnetic and thermal parameters should always depend on each other during the solution process. The method should evaluate the magnetic properties as a function of the temperature of the evaluated zone. Also, the analytic model to the magnetic problem should be able to employ non-linear material characteristics and non-linear solver capability.

Another factor is that, to shorten the simulation time and to obtain a more flexible model, the technique should be as less dependent on another simulation environment as possible.

4.2 Relevant Modeling Techniques

In the literature, there are numerous electromagnetic modeling techniques. This section summarizes commonly used analytical and numerical modeling techniques and compares with respect to the previously mentioned criteria.

4.2.1 Fourier Series (FS) Based Model

The main idea of this technique, which is also referred to as harmonic modeling, is expression of the magnetic scalar potential as a Fourier series expansion. In order to do that, the magnetic system is divided to different domains with respect to their material properties. The coefficients of the Fourier series are determined by equating the boundary conditions of the boundaries between these domains for each frequency component [16]–[18]. For source-free regions, the Poisson's equation can be formulated as:

$$\nabla^2 A = 0$$

For the domain cases which include a permanent magnet, this equation becomes:

$$\nabla^2 A = -\mu \nabla \times \vec{M}$$

where $\vec{M}$ is the magnetization vector of the permanent magnet.

The accuracy of harmonic modeling is adequate for the machine types with low magnetic saliency, and its computation time is quite low compared to the high-fidelity models. Thus, estimation of airgap flux density of air-cored or mildly salient machine topologies with Fourier series-based method provides satisfactory accuracy. On the other hand, introducing accurate non-linear material characteristics or temperature dependency lacks in this modeling technique.

4.2.2 Mode Matching (MM)

Mode matching method (also referred to as sub-domain method) is the primitive version of the harmonic modeling, The only difference between them is mode matching method is employed for homogeneous domains [19]. That is, slotted machine structures are not suitable for the use of this technique. Resultantly, introducing material-based properties to the model is not possible by adopting this technique.

4.2.3 Magnetic Equivalent Circuit (MEC) Model

This technique is one of the most common method to model the magnetic materials and is based on denoting the whole magnetic system as a reluctance network, similar to an electrical circuit. In this reluctance network, the passive magnetic elements are represented with reluctances, which is analogous to resistance in the electrical domain. The magnetic flux sources, such as the magneto-motive force (MMF) due to a coil or a permanent magnet, are shown with an MMF, or a flux source, whose electrical analogs are voltage and current source, respectively. The flux through each branch of the reluctance network can be simply found by the combination of Hopkinson's law, which is the magnetic counterpart Ohm's law; and the Ampère's law:

$$\Phi = \mathcal{F} \int_{l} \frac{\mu_0 \mu_r(l) S(l)}{dl}$$

MEC has several assets by means of model operation. The key advantage of MEC is its simplicity. Using this method, evaluation and solution of the magnetic systems are fast and easy. Also, having consisted of reluctance units, it is also possible to express the magnetic system both material and temperature-dependent. This enables the evaluation of non-linear magnetic properties, saturation characteristics of a certain material and temperature-dependent material properties. However, evaluating the topologies that require high precision may not provide satisfactory results by the use of MEC. To increase the precision of the model, the number of reluctance elements in the reluctance network can be increased, which would create a trade-off between accuracy and computation speed.

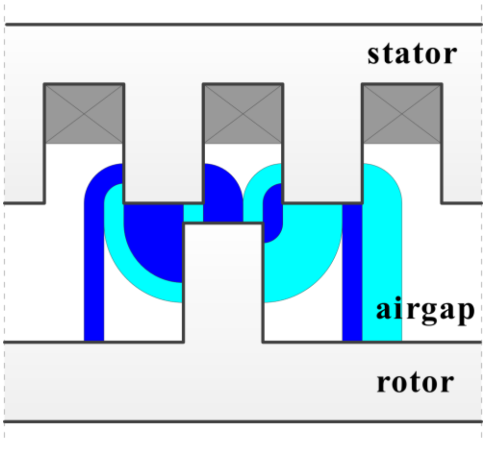


Figure 2: Visualization of flux tubes (shown in blue) in the airgap of a double salient machine, shown on a cylindrical coordinate system [20].

A more precise form of MEC is the tooth contour method (TCM). TCM is quite similar to MEC and it is built with reluctance components and flux tubes as well [20], [21]. The major difference of it is the reluctances of the flux tubes, shown as curved shapes in the airgap in Figure 2, are not pre-assumed rough shapes but are computed using electrostatic finite element method (eFEM). Even if this approach increases the accuracy of the model, it is dependent to another simulation environment and lowers the flexibility of the model.

4.2.4 Schwarz-Christoffel (SC) Mapping

Schwarz-Christoffel mapping is a conformal transformation method and is used to transform complex geometries to simpler shapes. This mapping is useful, especially for the analysis of slotted, magnetically salient structures [21]. With the use of this transform, airgap reluctance of such topologies can be simplified and can be represented as a slotless domain. Schwarz-Christoffel method is often combined with another semi-analytical modeling method to improve the accuracy of the model by employing the saliency effect. The most time-demanding part of this method, is to create stable (i.e. converging to a solution) conformal mapping scripts or integrating readily available automation scripts (e.g. in MATLAB).

4.2.4 Ampèrian Current (AC) Model

Ampèrian current model, or the equivalent current method models a magnetization vector in terms of an equivalent current density:

$$\overrightarrow{J_m} = \nabla \times \vec{M}$$

This modeling technique is often used to model the magnetization due to a permanent magnet in free space. The major advantage of it is that it can model the magnetic field in a 3D domain, without employing any mesh, boundary or discretization. Resultantly, it is fast and accurate for such problems. However, this method assumes a domain of relative permeability, μ_r, of 1. Because of this fundamental assumption, its use is very limited and this method is not suitable to integrate with any material properties, non-linear magnetic phenomenon [15], [22].

4.2.5 Coulombian Charge (CC) Model

Similar to the Ampèrian, the Coulombian charge model also models the magnetization vector in a free, 3D space. In this technique, the magnetization vector is written as an equivalent charge density:

$$\rho_m = \nabla \cdot \vec{M}$$

The same benefits and assets of equivalent current model also apply for the Coulombian charge model. In Figure 3a and 3b, the illustration of both representations are shown, respectively.

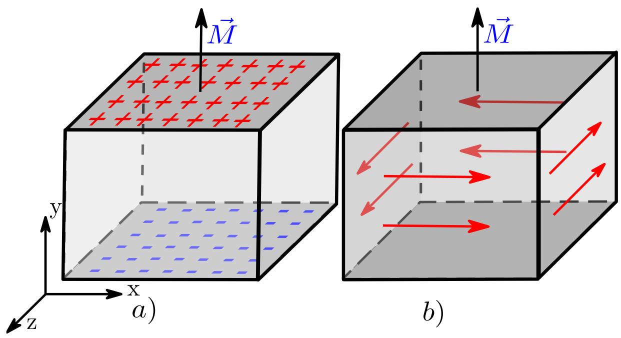


Figure 3: Illustration of a) Coulombian charge and b) Ampèrian current models [14]

4.2.6 Boundary Element Method (BEM)

Boundary element method is a numerical modeling technique which solves the Poisson's equation for discretized geometries. Its main principle is evaluating the integral of Poisson's equation on the boundaries of each discrete element, or mesh. Hence, for the magnetostatic problems in free space, BEM is a convenient and accurate tool [18]. Compared to the most commonly used numerical modeling technique, finite element method (FEM), it can obtain accurate solution by employing less number of elements. The major disadvantage of this modeling technique is its base assumption of linear and homogeneous magnetic field distribution inside a discretized element. Because of this, including non-linear characteristics of a material is not possible using BEM. On top of that, its computational burden is comparable to that of FEM, even if it employs less number of elements.

4.2.7 Finite Element Method (FEM)

Finite element method (FEM) is the most common numerical modeling technique in many areas that require solution to complex problems, such as fluid dynamics, heat transfer, mechanic analyses and electromagnetic analysis. Similar to BEM, it solves the Poisson's equation for each element of a discretized, or meshed domain. With FEM, magnetic scalar potential of each mesh element is calculated [18]. Also, non-linear material characteristics can be introduced to the model solver. FEM provides fairly accurate results, depending on the meshing density. However, increased accuracy and mesh density also increases the computational burden. The use of FEM in optimization processes would not be suitable for time limit concerns but it usually is used as a validation tool before overall evaluation and manufacturing processes. Currently, FEM is the most reliable analysis method despite being slow. Also various commercial electromagnetic analysis software that uses FEM are present [23]. Especially with these software, multiphysics simulation coupling of the electromagnetic models are suitable, yet, time consuming.

4.2.8 Hybrid Methods

Hybrid methods are often combined to obtain accurate semi-analytical models like FEM but are computationally less expensive than FEM. By combining two (or more) methods, the drawbacks of each of them can be compensated. Some of those possible combinations are MEC and harmonic modeling, tooth contour method and Schwarz-Christoffel mapping, mode-matching method and MEC. Hybrid models are especially useful for double salient machine topologies as both slotting effect and the material characteristics are required to be taken into account [24]. The only drawback of these modeling approaches is the implementation part. The building of these hybrid models, boundary definitions and coupled analysis is more time consuming and effort-required compared to the standalone semi-analytical modeling techniques.

In Table 1, the mentioned and explained modeling technique comparison is summarized with respect to both model development and model operation processes. In the table, "+1" denotes an advantage, "-1" denotes a disadvantage and "0" denotes neutral. (For a negative implication, such as model complexity,

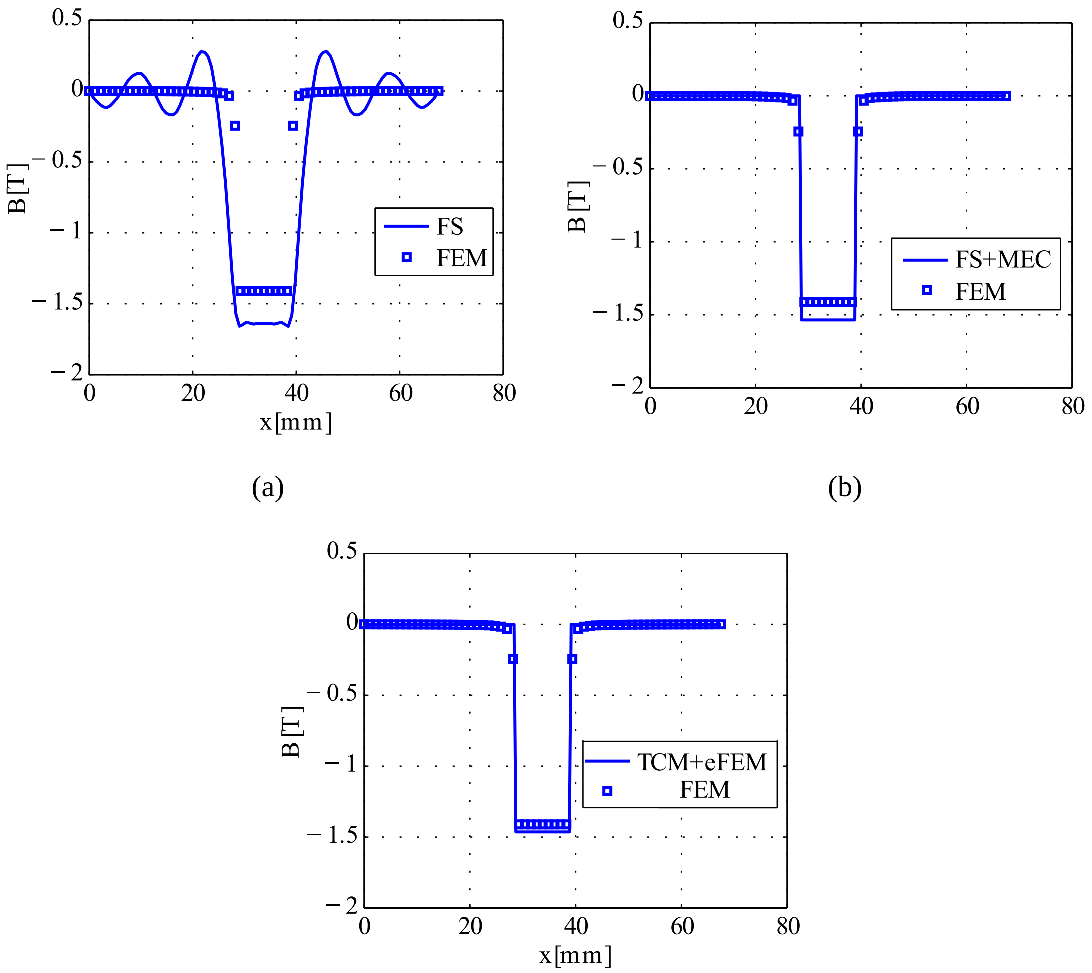
"+1" means that the relevant technique does not have that attribute, for example it is not complex.)

Table 1: Comparison of white-box modeling techniques

	Model Criterion	FS	MM	MEC	TCM(+eFEM)	AC	CC	BEM	FEM	FS+MEC	TCM+SC
Model Development	Model Complexity	+1	+1	+1	+1	+1	+1	-1	-1	-1	-1
	Power Scalability	+1	+1	+1	+1	+1	+1	0	0	+1	+1
	Model Flexibility	-1	-1	0	0	-1	-1	-1	-1	0	0
Model Operation	Material Dependent	+1	-1	+1	+1	-1	-1	+1	+1	+1	+1
	Temperature Dependent	-1	-1	+1	+1	-1	-1	-1	+1	+1	+1
	Model Accuracy	0	0	-1	0	0	0	+1	+1	+1	+1
	Evaluation Speed	+1	+1	+1	+1	+1	+1	-1	-1	0	0
	Co-simulation Requirement	+1	+1	+1	0	+1	+1	0	0	+1	0
Total Advantage Points		+3	+1	+5	+5	+1	+1	-2	0	+4	+3

Also on the bottom of the table, the total advantage points of each modeling technique is present. Thanks to its easy development procedure, intuitive structure, multiphysics integration capability and moderate accuracy, the tooth contour method seems to be the most suitable analytical modeling technique for the electromagnetic sub-unit of a traction motor digital twin. There are two drawbacks of this method: Its accuracy and its dependency on another simulation environment. Although in general those are major disadvantages, the accuracy enhancement with experimental data-driven black-box model and building the digital twin with the presence of an already realized design eliminate these drawbacks.

In Figure 4 below, the radial airgap flux densities of a double salient electrical machine obtained with several semi-analytical modeling techniques and FEM are shown. Figure 4a compares the FS method and FEM, and it proves that the harmonic method shows poor performance while calculating the airgap of the machines with high saliency. Figure 4b presents the same calculation obtained with a hybrid technique, where FS and MEC combined. This hybridization significantly improves the reliability of the modeling as it also includes the material-dependent (magnetic saturation) properties in the model. In Figure 4c, another hybrid modeling technique which is the combination of TCM and electrostatic FEM performance is shown. This method provides almost the same performance with FEM.



(c)

Figure 4: Comparison of normal airgap flux density calculations of a double salient machine with a) harmonic method (FS) and FEM, b) hybrid method (FS + MEC) and c) hybrid method (TCM + electrostatic FEM) and FEM [21]

5 Conclusion

In this work, a detailed comparative study is presented for the white-box modeling techniques, which can be used in the digital twin development of traction applications. A digital twin for the vehicle drivetrain, or a component level digital twin for the electrical machine of the vehicle is favorable to accelerate the design and test procedure of the vehicle components, since they are capable real-time simulation and evaluation. The main contribution of this study has been the comparison of the widely used analytical and numerical multiphysics models for the airgap flux density estimation required for an accurate torque estimation. The comparison is based on finding the most suitable modeling approach that can be represented as a simple state-space model with temperature and mechanical domain dependency. The study compared several commonly used analytical and numerical modeling techniques by means of their suitability for a digital twin as a white-box model. The comparison criteria were mainly related to model development and model operation. The least suitable methods were mode matching, Ampèrian current and Coulombian charge methods because of their lack of material property integrability. BEM and FEM were also not preferred because of their high computation power requirements. Even if the hybrid methods provide a good accuracy, the effort to build them is not feasible. It can be concluded that MEC and TCM are the most suitable approaches for digital twin development, thanks to their material property inclusion, simplicity and the capability to be enhanced with experimental data while building the grey-box model.

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Presenter Biography

Göksenin Hande Bayazıt received her BSc and MSc degrees in Electrical and Electronics Engineering from Middle East Technical University, Ankara, Turkey in 2018 and 2021, respectively. She is currently working towards her PhD degree in the Electromechanics and Power Electronics (EPE) Group of Electrical Engineering at TU Eindhoven, the Netherlands. Her research interests include analytical and numerical modeling of electrical machines, condition monitoring, fault tolerant machine topologies and their traction applications.

Esin Ilhan Caarls obtained her BSc in Electrical Engineering from Istanbul Technical University (ITU, Turkey) in 2007. With her work on solar-powered boats, she obtained a full TU Eindhoven scholarship, which lead to her MSc (2009) and PhD (2014) degrees in Electrical Engineering at TU Eindhoven. Her research focus is design of high-efficient electrical drives for traction applications. Since 2020, she has been working as a part-time Assistant Professor at TU Eindhoven.

Elena Lomonova received the MSc (cum laude), PhD (cum laude) degrees in Electromechanical Engineering, all from the Moscow State Aviation Institute (TU), Russia in 1982, 1993, respectively. She is currently full Professor and Chair of the Electromechanics and Power Electronics Group at TU Eindhoven. She has authored more than 250 scientific publications and more than 15 patents. She holds the prestigious awards – Nagamori (Japan, 2016) and Lifetime Contributions to Magnetics (UK, Cambridge, 2019). She has worked on the electromechanical actuators design, optimization and development of the advanced mechatronics systems.