Efficiency Map Versus Time-Stepping Solutions for Drive Cycle Performance Analysis of Permanent Magnet Synchronous Motors

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***Abstract*—Numerous research endeavours have examined the performance analysis of electric motors within drive cycles. Many have preliminarily focused on steady-state analysis to construct efficiency maps, which offer simplicity and time-efficiency. However, the accuracy of such maps in dynamic drive scenarios has remained unquantified. Additionally, there is a lack of exploration regarding the quantification of conventional efficiency maps compared to time-stepping solutions. This study addresses these gaps by investigating the disparities between grid-based efficiency maps and time-stepping solutions for a permanent magnet synchronous motor (PMSM) across various drive cycles. A laboratory based PMSM is used as an example test case machine, and standard drive cycles are down-scaled for laboratory testing. Steady state efficiency maps are obtained using finite element analysis and are compared with time-stepping solutions from direct laboratory measurements.**

***Index Terms*—Drive cycle performance, efficiency maps, finite element analysis (FEA), permanent magnet synchronous motor.**

I. Introduction

The development of highly energy-efficient vehicular power-trains is a global endeavor today, as carbon emissions are the common enemy [1]. The electrification of these power-trains is a prevalent practice, with the design of optimized electric machines, particularly permanent magnet synchronous motors (PMSMs), being a preferred choice due to their high torque and power density, high efficiency, and superior dynamic performance [2]. In comparison to conventional industrial applications where motors typically operate at one or a few predefined torque and speed points, modern electric motors for traction applications have to be studied for a wide range of possible torque/speed combinations within the motor's torque-speed envelope, so-called motor operating points (OPs). Different electric machines exhibit distinct operational characteristics, particularly under dynamic driving conditions, as each machine type offers unique advantages and trade-offs in terms of performance, efficiency, and cost [3]. Consequently, research has increasingly focused on the optimization of traction motor designs tailored to specific drive cycles [4]–[7]. While these methodologies achieve high accuracy for particular machine designs, they are not as successful in identifying key metrics that are necessary for broader practical adoption, like performance, cost, time, prototyping, and experimental validation.

Efficiency maps, crucial for illustrating traction motor performance, have been widely accepted. Usually, these maps are computed using finite element analysis (FEA) or equivalent circuit methods (especially in the case of induction motors) [8], [9]. The results from these methods are then verified with the experimentally obtained efficiency maps or performances [9], [10]. While the conventional methods are effective when detailed motor parameters are available, inaccuracies in the model parameters can cause performance prediction errors [11], [12]. This may not always be practical in large system simulations. Many researches aim to improve their computational efficiency and accuracy, typically through look up table (LUT) methods using FEA data. However, these maps lack precision for highly efficient motors, posing challenges in the detailed design phases [13]–[15]. Direct efficiency calculation from FEA using time-stepping methods is a promising alternative. Enhancing traction motor efficiency, even marginally, is a key research goal [16]. Yet, accurately quantifying the disparities between LUT methods, direct FEA-based approaches, and measurement based time-stepping results for torque-speed OPs remains a notable gap. Closing this gap is essential for defining the relative accuracy error confidently [17].

This paper compares the drive cycle performance of a laboratory scale PMSM using conventional methods with direct time-stepping measurement results across a full drive cycle. It evaluates the accuracy and effectiveness of these approaches in capturing real-world performance metrics. The accuracy of steady-state efficiency maps is quantified through direct comparison with measurement results. The study identifies the relative errors, assesses the computational time-accuracy trade-offs, pinpoints the significant disparities within the torque-speed envelope, and quantitatively analyzes these distinctions. The rest of the paper is organized as follows: Section II presents the state of art of the topic, Section III details the comparison between the steady-state efficiency maps and the direct FEA method, and Section IV provides the performance quantification by direct comparison with measurement results. Section V summarizes the main findings from the paper.

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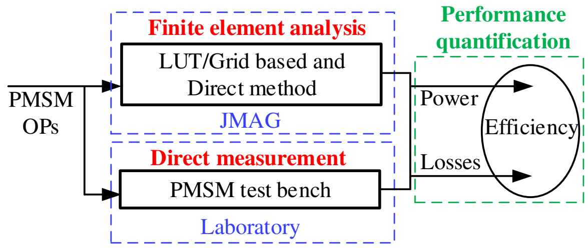

Fig. 1: Overview of the study.

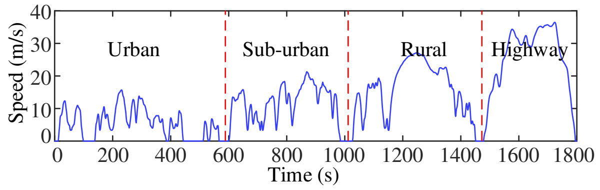

Fig. 2: WLTP cycle for class 3 vehicles [18].

II. State of Art

A laboratory scale small PMSM is used as a test case machine. Standard drive cycles are down-scaled to fit the PMSM's ratings using the down-scaling method presented in [19], and a baseline study is conducted to determine its OPs as detailed in [11] to assess it's performances. An example of the WLTP driving cycle as illustrated in Fig. 2 is presented in this paper. The LUT method based stady-state efficiency maps are created for a selected number of torque-speed grid points using FEA. The performance is quantified against direct measurement of the PMSM drive cycle OPs in the laboratory. A general overview of the study is given in Fig. 1.

A. FEA

FEA is used to calculate the drive cycle performance of the PMSM based on the LUTs and using direct computation of the OPs of the drive cycle. First, the LUT method based efficiency maps are created using the selected number of torque-speed grid points. Three different grids (rough and fine) with 199, 412, and 645 torque-speed grid points respectively are selected within the torque-speed envelope of the PMSM as shown in the Fig. 3. The points are selected in orderly manner within the speed range of 100 rpm to 8000 rpm and the torque range of 4 mNm and 0.15 Nm. For these grid points, the corresponding current vectors are generated for each torque-speed combination using the PMSM equivalent circuit model in MATLAB/Simulink [20] considering maximum torque per ampere (MTPA) control. These current vectors are then used for the steady-state FEA calculations using the JMAG software [21] with a 2D model of the PMSM. The results from the FEA calculations (such as powers and losses) are recorded, and these results are used to generate the corresponding efficiency maps in MATLAB. Using these maps as look up tables, the efficiency values of the PMSM drive cycle OPs are then obtained using the interpolation function (interp2) with the default linear interpolation method [22].

For the so-called direct method, all torque-speed combinations of the PMSM within the WLTP drive cycle are first simulated in MATLAB using the equivalent circuit model and MTPA control just like in the LUT based method. The current vector for each operating point is generated considering the current and voltage limits of the inverter in the laboratory. These current vectors are then directly used for 2D FEA to calculate the efficiency for each torque-speed combination of the drive cycle.

B. Laboratory Measurement

For the measurement of each drive cycle OP in the laboratory, the PMSM test-bench as shown in Fig. 4 is used. The PMSM studied here is torque-controlled and the load machine is speed-controlled. The WLTP drive cycle OPs of the PMSM are evaluated with the time-stepping approach with a time step of 0.5 second between each torque-speed point. For each OP, the powers at both the test machine's and the load machine's terminals are measured, and the corresponding efficiencies are calculated.

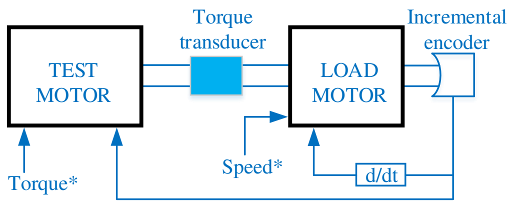

Fig. 4: Schematic of the PMSM test-bench in the laboratory.

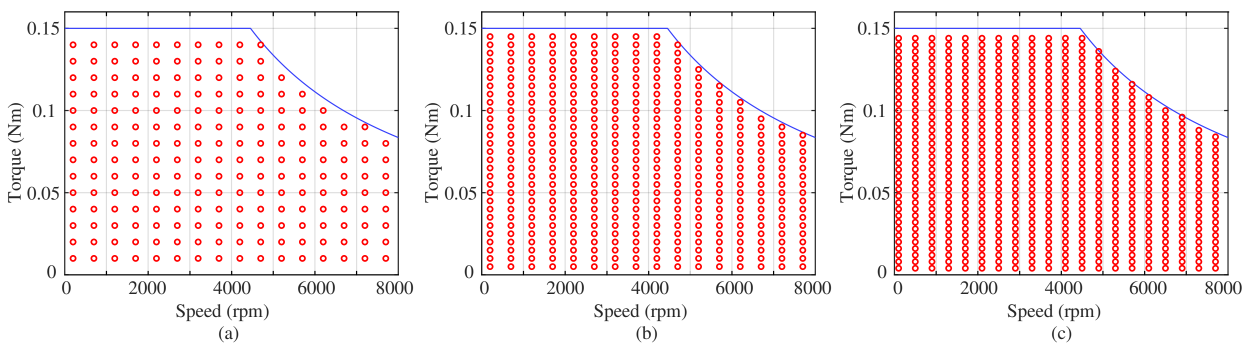

Fig. 3: Different torque-speed grids for the efficiency map computation using FEA with: (a) 199 grid points, (b) 412 grid points, (c) 645 grid points.

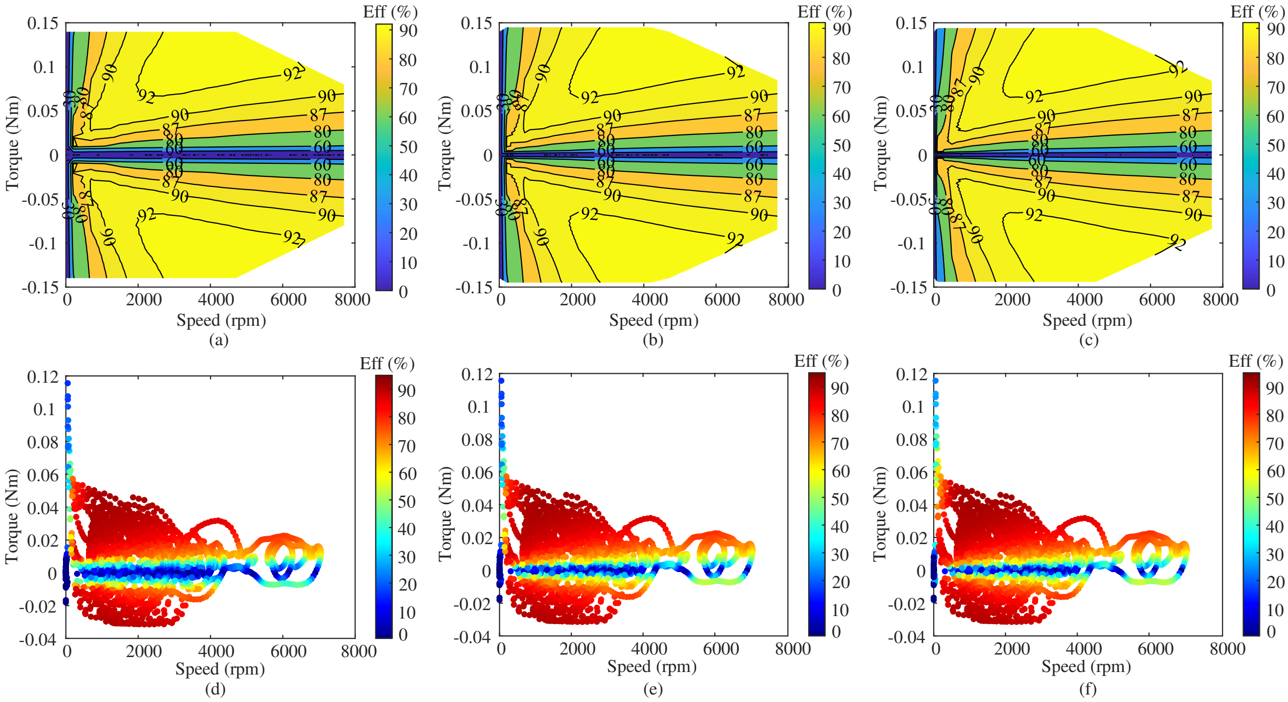

Fig. 5: Computed efficiency maps with different grid based points: (a) 199 points, (b) 412 points, (c) 645 points. Scattered efficiency plots of the PMSM OPs of the down-scaled WLTP drive cycle obtained using efficiency maps as LUT with: (d) 199 points, (e) 412 points, (f) 645 points.

III. Efficiency Maps Versus Direct Method

Drive cycle performance accuracy and computational time are investigated for the two different methods (LUT and direct). Table I shows the 2D FEA simulation times of different grid based points on a computer with 12th Gen Intel® Core™ i9-12900K, 3200 MhZ, 16 Core(s), 24 Logical Processors, and 64 GB RAM. Simulation of a single OP roughly takes about 35 seconds.

The efficiency maps are generated from FEA results using linear interpolation of the efficiencies values computed for each grid point. These maps serve as LUTs to determine the efficiencies for the drive cycle OPs of the PMSM. Since the selected grid points cover only the motoring region, the generating region's efficiency maps are derived by mirroring the motoring map. Fig. 5 shows the efficiency maps with different number of grid points and the corresponding efficiency plots of the PMSM OPs of the WLTP drive cycle. Already the visual inspection of these maps shows that the finer grid points result in the better map with smooth efficiency contours. The PMSM shows comparatively better performance in the medium torque-speed region. To understand how changing the number of grid points influences the computed overall drive cycle performance, the total root mean square error (RMSE) on the efficiency values of the PMSM OPs is calculated.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} |m_{\mathrm{i}} - s_{\mathrm{i}}|^2} \qquad (1)$$

The RMSE is normally used to quantify the average magnitude of differences between two sets of data [23]. It is computed using (1), where N represents the total number of data points, m_{i} denotes the efficiency of each PMSM operating point for the WLTP drive cycle based on the LUT method with different number of grid points, and s_{i} represents the corresponding values from the direct FEA method.

TABLE I
Study Method and Simulation Time

Study method	OPs	Simulation time
Grid based or LUT	199	2 hours
Grid based or LUT	412	4 hours
Grid based or LUT	645	6 hours
Direct FEA	3600	31 hours

The RMSE of the LUT based method compared to the direct FEA computation of the drive cycle's OPs is 11.28% with 199 grid points, 6.01% with 412 grid points, and 4.41% with 645 grid points. Doubling the grid points approximately halves the RMSE at doubled computational time, showing an anti-proportional relationship. The majority of these errors are seen for the PMSM OPs when the motor is accelerating or decelerating rapidly. The average errors compared to the direct solutions are as high as 20% and roughly below 2.3% in the case of rapid deceleration and rapid acceleration, respectively. Moreover, larger differences occur in the low torque and high speed as well as high torque and low speed regions. A rough grid fails to define the torque-speed points accurately and thus the efficiency values need to be interpolated, which leads to additional interpolation errors. As the grid becomes finer, the average error decreases.

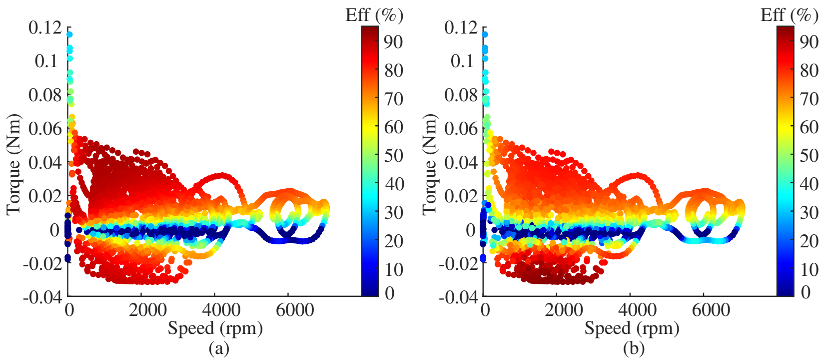

Fig. 6: Scattered efficiency plots of the PMSM operating points of the down-scaled WLTP drive cycle obtained using: (a) direct FEA method, (b) laboratory measurement.

TABLE II
ERROR ANALYSIS OF DIFFERENT METHOD WITH MEASUREMENT RESULTS

Method	Full drive cycle	Drive cycle regions			
		Low speed (urban)	Medium speed (sub-urban)	High speed (rural)	Extra-high speed (highway)
LUT (199 points)	15.39%	17.27%	15.83%	15.86%	11.03%
LUT (412 points)	12.29%	16.67%	13.32%	12.76%	7.60%
LUT (645 points)	11.82%	16.80%	13.18%	12.49%	7.42%
Direct FEA	11.53%	18.04%	13.71%	12.77%	7.34%

IV. COMPARISON WITH MEASUREMENT RESULTS

The PMSM was experimentally tested at different OPs of the down-scaled WLTP drive cycle. The corresponding stator voltages, currents, torques, and speeds were recorded, and the efficiencies were calculated from the measured input and output powers. Fig. 6 shows the scattered efficiency plots of the PMSM OPs obtained both by direct FEA and from the laboratory measurements. The laboratory measurements show comparatively lower efficiencies, especially for the medium torque-speed OPs. This is mainly due to the inadequate modelling of the exact losses, including no load losses, frictional losses, and iron losses by the FEA method.

To assess the accuracy and quantify the errors of the methods presented in comparison to the experimental results, the RMSE was calculated as per (1). This time, N again represents the number of data points, m_i denotes the efficiency of each PMSM operating point obtained using the respective FEA methods, and s_i represents the corresponding efficiency obtained from the direct experimental test. The computed errors are shown in Table II. Doubling the grid points doesn't reduce the overall error by half. In fact, with doubled grid points, the overall drive cycle error reduced by roughly 20% and with three times the grid points, the overall error reduced roughly by 25%. This indicates that the accuracy does increase with grid density, and so does the computational time, however, it also indicates that the accuracy doesn't always increase proportionally with the grid density. There is an optimal number of grid points that needs to be considered above which the added effort does not translate into the same increase of accuracy. This emphasizes the necessity of a good trade-off between accuracy and computational time. The direct FEA method exhibited smaller error than the LUT based approaches, however, the difference is not significant given the added computational time for the direct FEA approach. Moreover, there are additional losses that couldn't be accurately predicted or modeled with respect to the measurement tests (as this is the general case especially with small machines of the size of the PMSM studied here), which contributed to the overall error in the direct comparison.

To quantify the performance of the PMSM OPs during a dynamic driving scenario more in detail, the RMSEs for different regions of the WLTP drive cycle were calculated additionally. As illustrated in Fig. 2, the WLTP mainly consists of four regions representing a balanced combination of low speed (urban), medium speed (sub-urban), high speed (rural), and extra high speed (highway) driving conditions. During high-speed phases of the drive cycle, the errors are significantly lower compared to the low and medium speed regions. The direct FEA method resulted in comparatively lower errors in the high speed region and higher errors in the low and medium speed regions. In addition to the software constraints and interpolation errors, transient factors such as acceleration and deceleration conditions (drive dynamics) make efficiency prediction erroneous in these regions. Additionally, the frictional losses influenced by the test-rig configuration, which do not have a linear relationship with the motor speed, but rather a parabolic one, further amplify these discrepancies.

V. CONCLUSIONS

This paper studied and presented the results on the quantification of drive cycle performance of a laboratory scale small PMSM using conventional steady-state efficiency maps and direct time-stepping laboratory measurement results. The LUT-based method indicates that doubling the grid points nearly halves the overall error when compared to the direct FEA results. In contrast, the comparison results with the time-stepping measurement method show that the errors do not decrease noticeable beyond a certain number of grid points, indicating the occurrence of an optimal grid density for best performance results.

The LUT based method, which requires precise modeling of losses, demonstrates good accuracy and computational efficiency if an optimal grid density is selected. Although the direct FEA method offers detailed electromagnetic analysis, it is computationally intensive and impractical for timely solutions. Errors in both methods, when compared to the measurement results, are primarily due to imperfect loss modeling, especially in low and medium-speed regions and transitions to high-speed regions.

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ChatGPT 3.5 [24] has been used for editing and grammar enhancement of the paper. The paper has been subsequently edited manually again.

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