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Investigation on Effect of Nonlinear Parameters in Torque Accuracy of Permanent Magnet Synchronous Machines

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Abstract

EVs and PHEVs are mainly driven by inverter control topologies which will be driving permanent magnet synchronous machines. PMSM is widely used for high drive performance. However, due to parameter variations high torque accuracy is not achieved. The performance of the PMSM drives is widely affected which is caused mainly due to environmental factors and aging. This would include component tolerance, input signal tolerance, machine parameters, software algorithms, sensor accuracy and calibration. It is important to understand these factors and make the tuning throughout the lifecycle since it may show performance deviations over the time and may lead to field complaints.
As a step-by-step procedure, the factors which affects the torque accuracy are identified as part of the literature review. This is given as input to a cause effect relationship model which could demonstrate the deviation points. Simulation is performed by varying the operating points at different regions in the e-drive system modeled in Matlab/Simulink. Simulation results are used with different operating points to find out the influential parameters contributing to the deviation.
The outcomes derived from the simulations are analyzed and dominant factors are determined. It is observed that this behavior will vary according to the changes in speed and torque. Correlation coefficient is derived from the statistical analysis. The future scope will be applying the optimization techniques and verification of improvements.

Keywords: EV, PMSM, Torque accuracy, Field oriented control

1. Introduction

Inverter control topologies mainly drive EVs and PHEVs, which then power permanent magnet synchronous machines. PMSM is commonly employed for achieving excellent drive performance. Nevertheless, high torque accuracy is not achieved because of parameter variations. Environmental factors and aging mainly contribute to the necessity for parameter changes, significantly impacting the overall system performance. This would encompass component variability, signal input range, machine settings, software calculations, sensor precision, and calibration. Understanding these factors and adjusting throughout the lifecycle is crucial as performance deviations may occur over time, potentially resulting in customer complaints in the field. In the literature review, the factors influencing torque accuracy are identified systematically. This input is provided to a model that shows cause and effect relationships and can display points of deviation. Different operating points are utilized in simulation results to identify the influential parameters causing the deviation. Estimation and adaption techniques are available for several parameters which affects the torque accuracy. Based on the complete operating region, techniques need to be developed for the suitable application of the same with periodic online updates. Accuracy in torque control is crucial for optimal performance and efficiency in electric vehicles (EVs), especially in permanent magnet synchronous machines (PMSMs), which are commonly used in EV propulsion systems due to their high efficiency and power density. Addressing these factors can enhance torque accuracy in PMSMs used in electric vehicles, leading to improved performance, efficiency, and overall driving experience. The objectives would be to determine the parameters affecting E Machine torque accuracy, run simulations at different operating points, determine the dominant factors and application of online tuning parameters which came up as part of literature study.

2. Machine and Control

PMSM field-oriented control is a popular technique dealt with hybrid and electric vehicle applications. Feedback from different sensors is taken to a control strategy which is used to generate the PWM pulses which in turn controls gate drivers and IGBT switching. Depending upon the setpoints of speed/torque control, suitable switching technique is chosen. PMSM properties enable us to separate the flux and torque component of current which will help further to optimize its operation at the given points. Until a particular rotation speed, the torque stays constant as speed increases which is called constant torque region. After the rated speed, the torque starts ramping down with increase in speed which is known as constant power or field weakening region.

3. Permanent Magnet Synchronous Motor

The dc excitation of the field winding in a synchronous machine can be provided by permanent magnets. The main advantages of replacing the electrical excitation with permanent magnets are eliminating the copper losses, reducing the weight and size and a simpler construction for the same performance with reduced losses and thus high efficiency compared to the dc.

On the other hand, a disadvantage is that at present prices, permanent magnet materials are relatively high, and the magnet characteristics change with time. The PMSM equations which are used for predicting its transient behavior are summarized as follows. The machine equations are referred to the rotor reference frame assuming a sinusoidal distribution of the permanent magnet flux in the stator in [1].

$$\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} \omega_r i_q \qquad -(1)$$

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} \omega_r i_d + \frac{\lambda \omega_d}{L_q} \qquad -(2)$$

$$T_e = 1.5P \, [\, \lambda i_q + (L_d - L_q)\, i_d i_q \qquad -(3)$$

$$\frac{d}{dt} \omega_r = \frac{1}{J}(T_e - F\omega_r - T_m) - (4) \qquad -(4)$$

L_d, L_q = q and d axis inductances, R = stator winding resistance, i_d, i_q = d and q axis currents, v_d, v_q = d and q axis voltages , ω_r = angular velocity of the rotor, λ = amplitude of the flux induced by the permanent magnet of the rotor in the stator phases, P = number of poles . T_e = electromagnetic torque, J = inertia constant, F = viscous friction of the rotor , T_m = shaft mechanical torque

4. Performance dependent factors of electromagnetic torque

The torque of permanent magnet synchronous machines (PMSM) is essentially controlled by supplying the machine with suitable stator currents. For most gearboxes that operate speed control, a fixed conversion between torque demand and stator currents can be used, as the external speed control loop compensates for model inaccuracies. However, there are some applications where actual torque must be controlled, and an external speed control loop cannot be used. In hybrid transmissions with mechanical power distribution, the transmission speed is determined by the speed of the vehicle. In this case, the power distribution must be controlled by the torque of the electric drive. Another example is a single-wheel drive, where the torque of each engine is controlled separately, e.g. to stabilize vehicle dynamics. In most cases, the torque of the machine is not measured. in these applications. Open loop torque control strategies based on torque current dependence models must be used. Any error in the model reduces the effectiveness of the underlying action strategy. In the first example, the power distribution of the hybrid transmissions would deviate from the desired ratio. In another example, the stabilizing effect of torque control on vehicle dynamics may be compromised. Accurate torque is essential in these applications. Idealized machine models based on biaxial theory lead to a imple relationship between flow and torque. The degree of idealization is high in this case, which leads to torque prediction errors. It is possible to extend the idealized models to consider many parasitic effects. In such models, parameters such as inductances and flux linkages are dependent on current, rotor position and other properties. The torque prediction error of such models is determined by the uncertainties of the underlying magnetic field calculation. There are few studies, which examine the influence on torque for certain single parameters and effects.

As mentioned in [2], PMSM showed higher dynamic response and efficiency. Torque regulation is almost the same. Speed is achieving steady state quickly in PMSM. [3] describes various factors which affects the performance of PMSM. Saturation influence on the torque is also described in [4]. In [5], a relative torque error of up to 30% is stated for a certain machine design. For a different design, the maximum torque error due to saturation is identified to 5% by [6]. The significance of the influence of saturation on Maximum-torque per- Ampere (MTPA) control strategies is shown e.g., in [7]. Yet, the studies do not include the influence of different machine designs. Further, it is not discussed which material properties are responsible for the influence of saturation on torque. Therefore, it is difficult to evaluate the accuracy of the control strategies.

5. Need and approach for torque accuracy improvement

Simulating torque accuracy in MATLAB Simulink involves creating a model that represents the system where torque accuracy is critical and then analyzing the behavior of torque measurements or estimations within that system.It includes the steps right from modelling the system considering the factors derived in chapter 2 and performing the structured analysis to find out the deviations. Here's a general outline of the system used.

5.1 Approach

1. Modeling the System:

- Identify the system where torque accuracy is important
- components such as motors, sensors, controllers, and any other relevant elements.

2. Torque Measurement or Estimation:

- Using mathematical models, observers, or filters to estimate torque based on other measurable quantities like current, voltage, or position.

3. Introducing Accuracy Factors:

- introduce factors that affect accuracy. This could include sensor noise, modeling errors, or disturbances in the system.
- Incorporate these factors into your model to realistically simulate the accuracy of torque measurements or estimations.

6. Simulation and Analysis

Run simulations in Simulink to observe the behavior of torque accuracy in different scenarios.

Analyze simulation results to understand how accuracy is affected by various factors such as noise levels, modeling errors, or system disturbances.

The approach here would be to consider the affected parameters for torque accuracy as given in Figure 6.1 which includes the physical inputs like voltage, current, temperature and rotor position. All these will be used to calculate the electromagnetic torque. Also, the parameter settings play a major role here as well. It includes the machine and sensor parameters as well. The behavior by setting of the parameters can vary due to ageing and environmental factors. There would be production tolerances which can affect here as well. Also with the control part, the steady state behavior of current controller and modulation strategy which was chosen also can affect the torque tolerance between the desired torque and actual torque. This will be given to the existing model under different operating points and the deviation between desired torque and actual torque will be analyzed. Figure 3.2 represents the dominant factors which can affect the torque accuracy in sensor and E-machine parameter point of view.

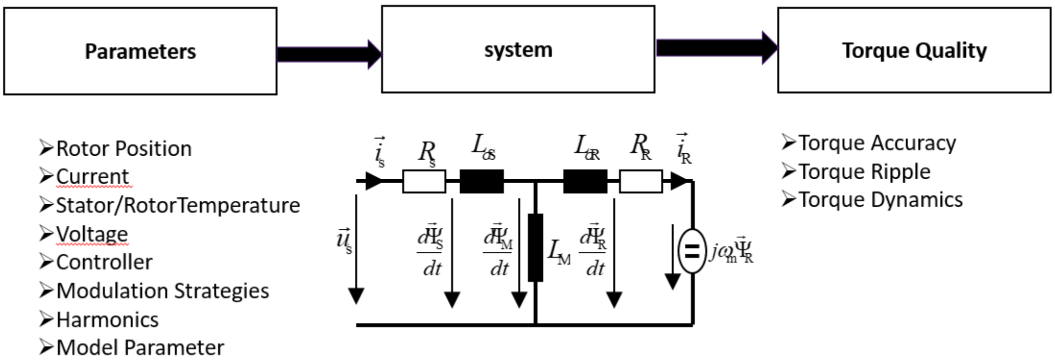


Figure 6.1 Torque tolerance representation

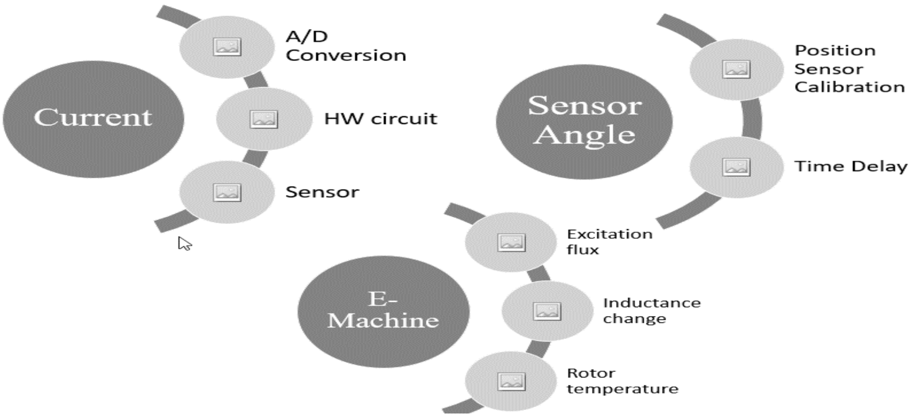
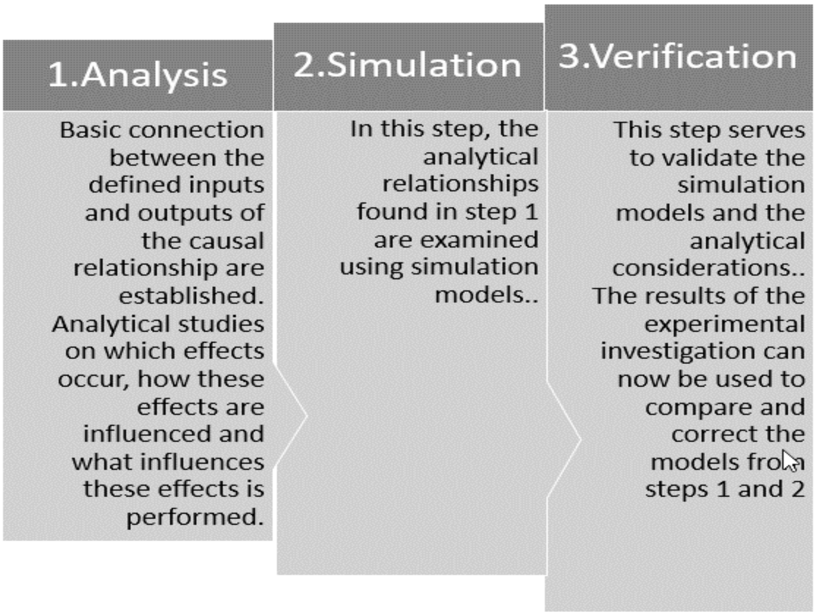


Figure 6.2 Factors which affect torque tolerance.

6.1 Finding the dependent factors from cause effect relationship model.

The implementation of simulation is performed in a cause effect relationship model of the electrical powertrain, consisting of components as machine, inverter, battery etc. Depending upon the environmental conditions, the transient behavior of a system can be simulated. It has the provision to give the inputs for electric drive train such as voltage setpoint, speed/torque demand/setpoint depending upon the control mode, failure scenarios etc. In this context, the use cases with different speed and torque are simulated in a predefined operating point and simulation results are obtained.

As given in Figure 3.3, the analysis part on what is the requirement is identified as described in section 3.1. Each effect have covered as part of literature study how it will be affecting the given system.In other words, a cause effect relationship will be established as the first step.Once this is done , the inputs are given to a simulation model which is capable of analyzing the modelled data agaist the experimental data which will provide you the required comparisons at various setpoints and it’s analytical relationships. We can set the number of iterations and te duration such a way that the depending behavior can be identified.As a last step , the verification of analyzed data needs to be done which comprises of the simulation model and analytical considerations. This data can be further used to correct the model parameters in the way which the requirements needs to be fulfilled.



1.Analysis

Basic connection between the defined inputs and outputs of the causal relationship are established. Analytical studies on which effects occur, how these effects are influenced and what influences these effects is performed.

2.Simulation

In this step, the analytical relationships found in step 1 are examined using simulation models..

3.Verification

This step serves to validate the simulation models and the analytical considerations.. The results of the experimental investigation can now be used to compare and correct the models from steps 1 and 2

Figure 6.3 Cause effect relationship model

6.2Simulation and calculation of torque

The following represent the field-oriented control loop which is given in Figure 4.1. The torque demand from vehicle control unit will be received at the e-Drive system. The desired torque is calculated by converting the torque demand to Id-Iq with the help of lookup tables. The actual torque will be also determined in parallel to the feedback loop with the current sensor. The following E-drive system is modelled in MATLAB-Simulink.

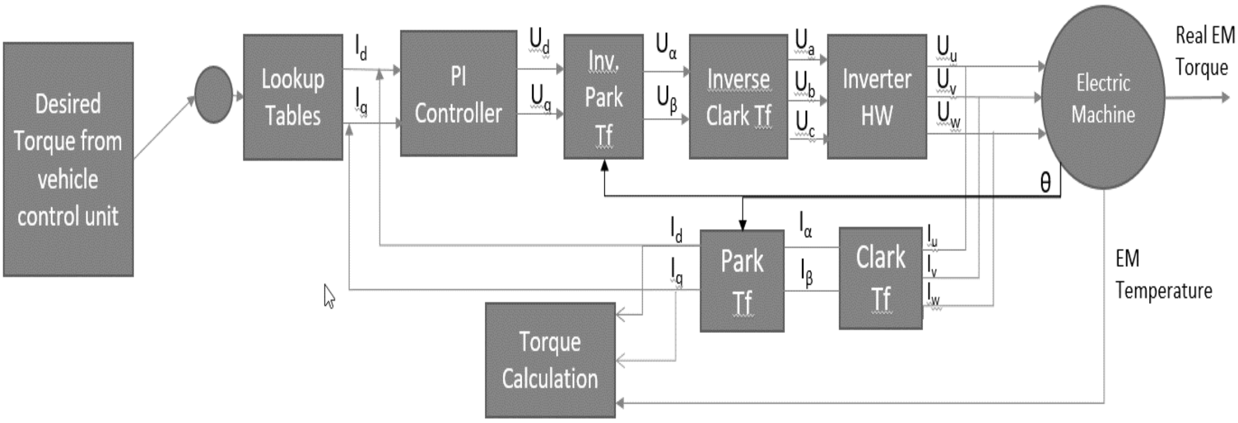


Figure 6.4 e-Drive simulation Control blocks

For calculating the desired torque, the torque received from external vehicle control unit is considered. Out of this, desired q axis current is calculated which is responsible for the generation of the torque. This is represented in Figure 4.2.

Actual torque is determined based on the voltage, speed, temperature, and current sensor inputs. It calculates flux from i_d, i_q, inductance and resistance which calculates the electromagnetic torque. This is represented in Figure 4.3

6.3. Results

Inverter module temperature is observed as varied from 20°C up to 150°C.Stator temperature and Rotor temperature kept at 20°C. HV voltage of 350V is given and constant PWM frequency of 10KHz is set.

Simulations are performed by varying speed from 1500 rpm to 14000 rpm and torque from 25Nm to 400 Nm. At higher speeds, torque deviation is mainly affected by offset angle of position sensors. At higher torques, torque deviation is mainly affected by increasing offset of current sensor and change in flux. Correlation coefficient is derived which reflects how similar the measurements of two or more variables are across a dataset.

Trend in torque accuracy deviation

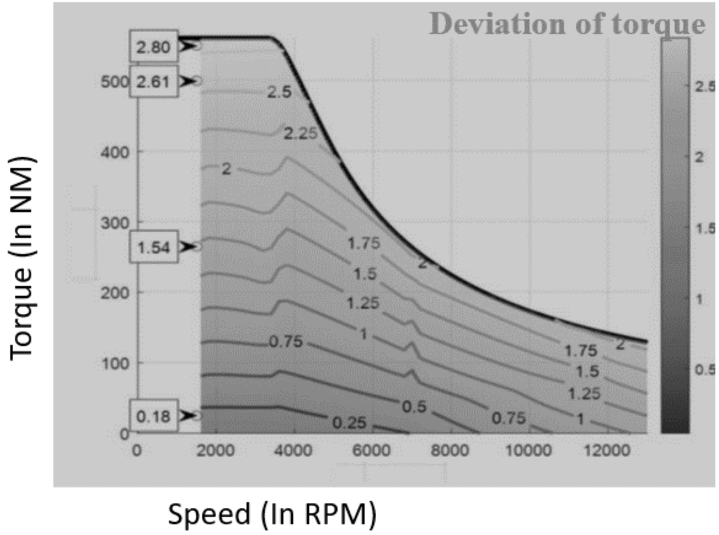


Figure 4.4 Torque deviation at multiple operating points

- **Low speed and high torque setpoint : At (3000 rpm, 200 Nm)**

Factor	Correlation coefficient
Position sensor offset	0.009807
Current sensor gain	0.2928
Inductance difference	0.258
Rotor temperature	0.0033
Excitation flux	0.7537

Table 4.1 Correlation coefficients operationg point 1

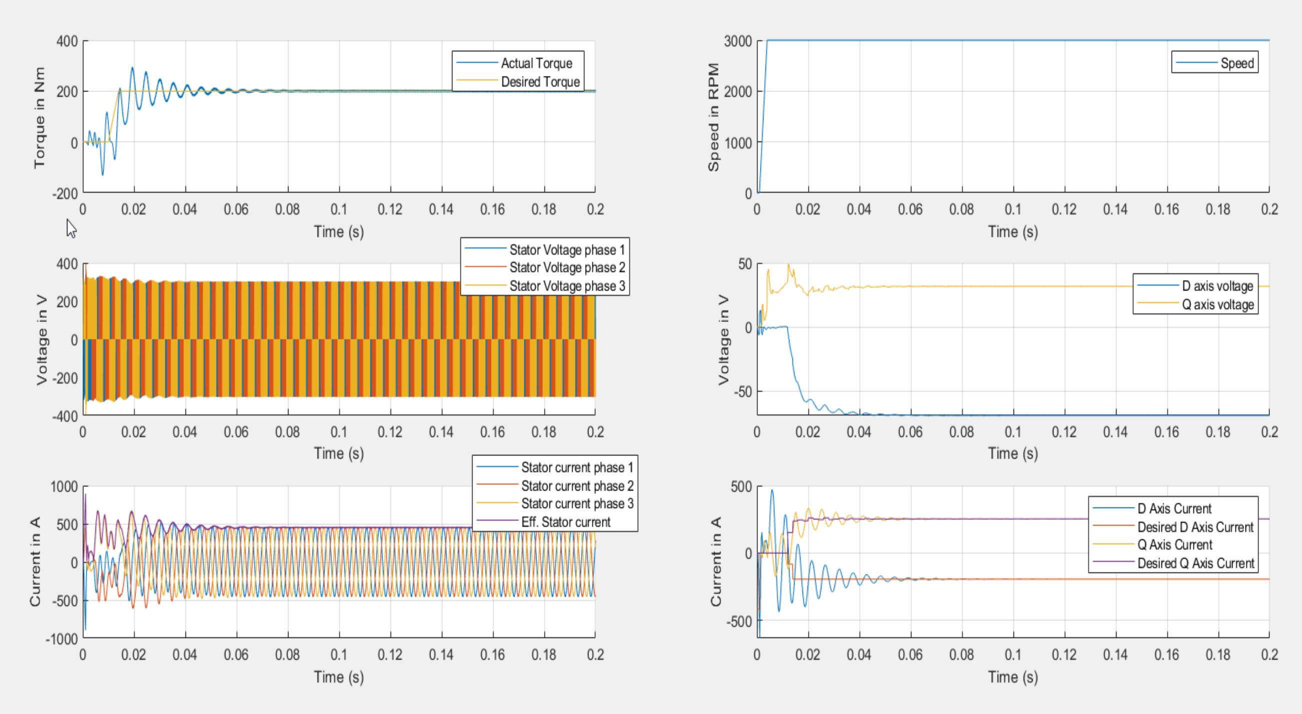


Figure 4.5 Result Operating point 1

- **High speed and low torque sepoint : At (13000 rpm, 60 Nm)**

Factor	Correlation coefficient
Position sensor offset	0.9435
Current sensor gain	0.0916
Inductance difference	0.0943
Rotor temperature	0.0159
Excitation flux	0.2104

Table 4.2 Correlation coefficients operationg point 2

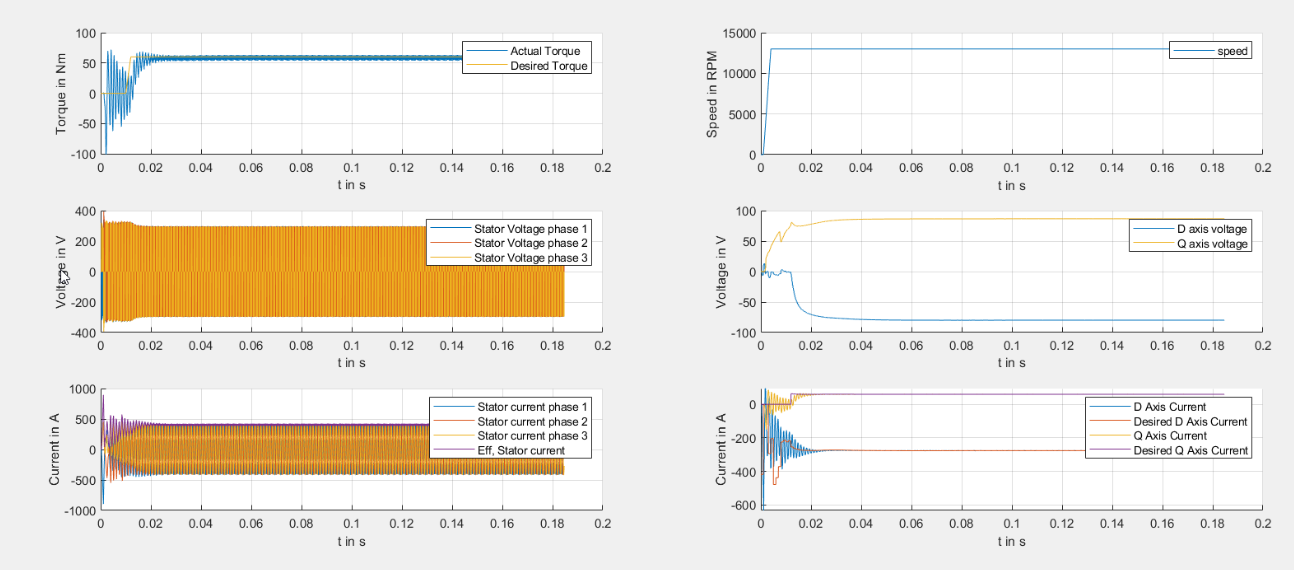


Figure 4.6 Result Operating point 2

- **Low torque and low speed setpoint : At (1500 rpm, 25 Nm)**

Factor	Correlation coefficient
Position sensor offset	0.04761
Current sensor gain	0.2194
Inductance difference	0.0056
Rotor temperature	0.0500
Excitation flux	0.8917

Table 4.3 Correlation coefficients operationg point 3

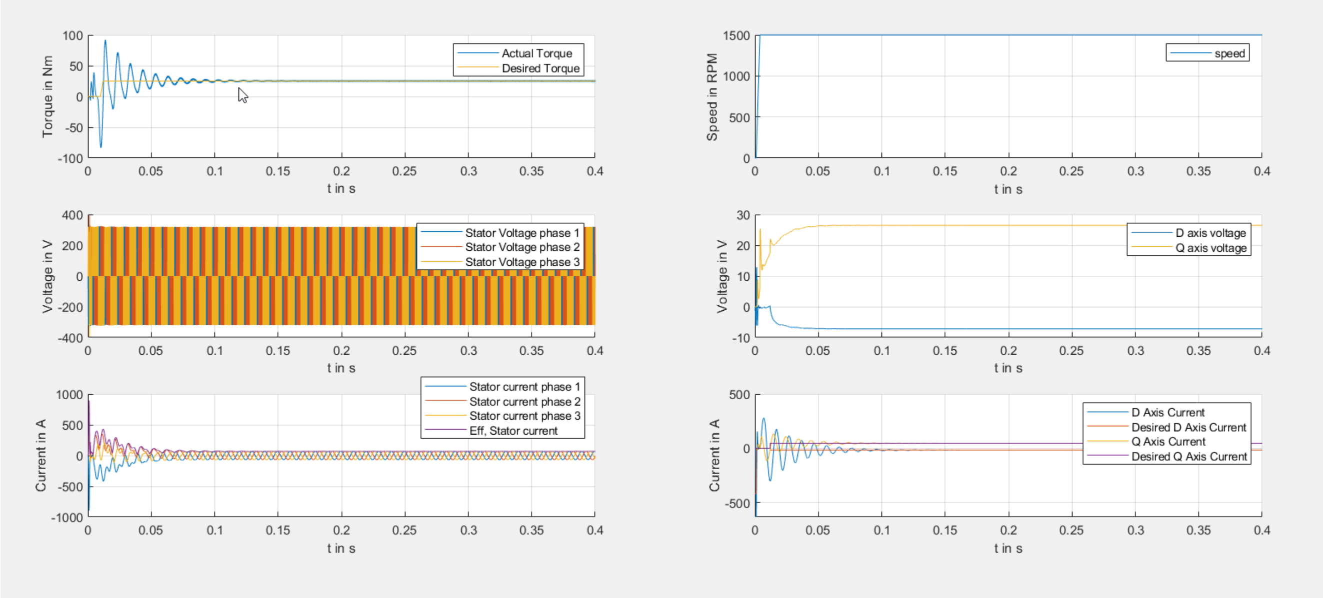


Figure 4.7 Result Operating point 3

- **High torque and high speed setpoint : At (13000 rpm, 130 Nm)**

Factor	Correlation coefficient
Position sensor offset	0.9184
Current sensor gain	0.1407
Inductance difference	0.1549
Rotor temperature	0.0153
Excitation flux	0.1732

Table 4.4 Correlation coefficients operationg point 4

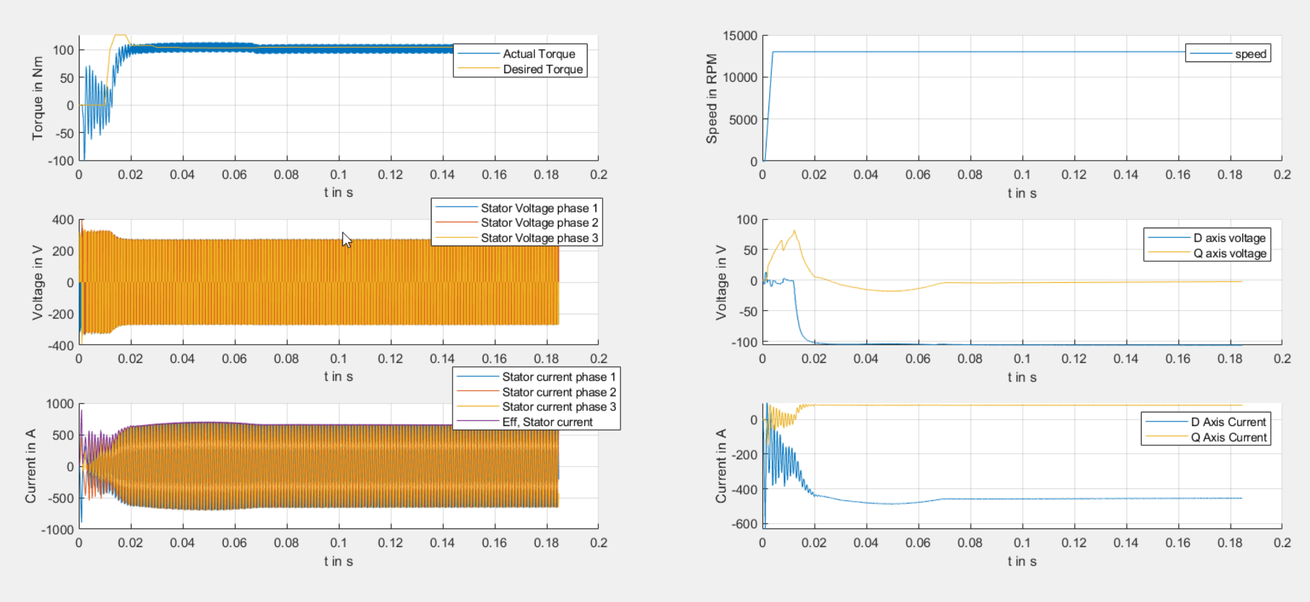


Figure 4.8 Result Operating point 4

7. Conclusion and future work

It has been successfully able to simulate the difference with the desired and actual torque referred from literature in an established E-drivetrain Simulink model and the differences in the output were observed as well. The upcoming challenges would mainly be Designing control algorithms tailored to improve torque accuracy in PMSMs. Completion of simulation and tests.

This would have still room for further investigations with analysis of experimental data to identify sources of error and areas for improvement. Fine-tune control parameters, sensor configurations, or hardware components to optimize torque accuracy further.

While inverters have become significantly more efficient, there is ongoing research to further improve their conversion efficiency, reducing energy losses and increasing overall system performance. Depending upon the operating point, variable switching frequency techniques are a possible way forward where the optimal technique can be chosen based on the demand. Angle synchronous methods are also getting into the field in addition to the time synchronous methods which has a future scope as well. Next steps would be to continue the investigation and enhance it to different types of machine models, covering various operation region.

8. Conflict of Interest

This work was supported by Bosch Global Software Technologies.

9. References

1. A. Thul, B. Groschup and K. Hameyer, "Influences on the Accuracy of Torque Calculation for Permanent Magnet Synchronous Machines," in *IEEE Transactions on Energy Conversion*, vol. 35, no. 4, pp. 2261-2268, Dec. 2020, doi: 10.1109/TEC.2020.3009490
2. A. Chinthala and S. Vuddanti, "Performance Analysis of Induction Motor and PMSM for Electrical Vehicle Traction Application," *2022 IEEE International Conference on Distributed Computing and Electrical Circuits and Electronics (ICDCECE)*, Ballari, India, 2022, pp. 1-6, doi: 10.1109/ICDCECE53908.2022.9793305.
3. Mercorelli, Paolo. 2023. "Identification of Parameters and States in PMSMs" *Electronics* 12, no. 12: 2625
4. Z. Li and H. Li, "MTPA control of PMSM system considering saturation and cross-coupling," *2012 15th International Conference on Electrical Machines and Systems (ICEMS)*, Sapporo, Japan, 2012, pp. 1-5.
5. M. M. Bech, T. S. Frederiksen and P. Sandholdt, "Accurate torque control of saturated interior permanent magnet synchronous motors in the field-weakening region," *Fourtieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, 2005.*, Hong Kong, China, 2005, pp. 2526-2532 Vol. 4, doi: 10.1109/IAS.2005.1518815.
6. A. Soualmi, F. Dubas, D. Dépernet, A. Randria and C. Espanet, "Inductances estimation in the d-q axis for an interior permanent-magnet synchronous machines with distributed windings," *2012 XXth International Conference on Electrical Machines*, Marseille, France, 2012, pp. 308-314, doi: 10.1109/ICElMach.2012.6349882.
7. A. Rabiei, T. Thiringer, M. Alatalo and E. A. Grunditz, "Improved Maximum-Torque-Per-Ampere Algorithm Accounting for Core Saturation, Cross-Coupling Effect, and Temperature for a PMSM Intended for Vehicular Applications," in *IEEE Transactions on Transportation Electrification*, vol. 2, no. 2, pp. 150-159, June 2016, doi: 10.1109/TTE.2016.2528505
8. K. Inomata, A. Yamazaki, Y. Hamabe and H. Hara, "Improvement of PMSM Torque Accuracy with On-line Estimation of Permanent Magnet Flux Linkage and q-axis Inductance," *2020 23rd International Conference on Electrical Machines and Systems (ICEMS)*, Hamamatsu, Japan, 2020, pp. 349-354, doi: 10.23919/ICEMS50442.2020.9290935.
9. Wen, Bisheng, Kan Liu, Jing Zhou, Shichao Zhou, Wei Hu, Yongdan Chen, Chao Huang, and Qing Huang. 2022. "Real-Time Estimation of PMSM Rotor Flux Linkage for EV Application under Steady State and Free-Running Conditions" *World Electric Vehicle Journal* 13, no. 5: 83
10. Y. Min, W. Huang, J. Yang and Y. Zhao, "On-line Estimation of Permanent-magnet Flux and Temperature Rise in Stator Winding for PMSM," *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)*, Harbin, China, 2019, pp. 1-5, doi: 10.1109/ICEMS.2019.8922250.