Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 119 (2023) 1246–1251

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

A Holistic Design Approach to the Mathematical Modelling of Induction Motors for Vehicle Design

Sai Kausik Abburu[a,*], Carlos Casanueva Perez[a], Ciarán J. O'Reilly[a]

[a] KTH Royal Institute of Technology, The Centre for ECO2 Vehicle Design, SE-100 44 Stockholm, Sweden

* Corresponding author. Tel.: +46-7697803559. *E-mail address:* abburu@kth.se

Abstract

In early-stage vehicle design, there is a significant lack of knowledge about the impact of design requirements on the design of subsystems, the resulting knock-on effects between subsystems and the vehicle's overall performance. This leads to a sub-optimal vehicle design with increased design iterations. To mitigate this lack of knowledge, a cross-scalar design tool consisting of an induction motor model is presented in this paper. The tool calculates the motor's attributes, namely its volume, mass, and the performance it can deliver to satisfy a given drive cycle's requirements. This is achieved by breaking down the drive cycle requirements into motor parameters from which the various power losses are derived. These key losses are then utilised to develop the torque/speed curve. Furthermore, it is proposed that the motor's attributes can be used to design other subsystems and consequently analyse their interaction effects. For example, the motor's attributes can be used to design regenerative brakes and consequently analyse their influence on brake wear, lifetime, and energy savings. Thus, the design tool enables the design of efficient vehicles with minimised design iterations by analysing the influence of design requirements on the subsystem's design and the consequent interaction effects among the subsystems and on the vehicle's overall performance.

Keywords: Early-stage design; Design tool; Subsystem Interaction; Induction Motor Model.

1. Introduction

With the increasing need to reduce greenhouse gas emissions and energy usage of vehicles, the vehicle industry has shifted its goal towards developing sustainable and efficient solutions. However, this shift entails the need to reformulate the approach to designing vehicles, as the conventional approach to vehicle design is conservative and possibly biased [8].

In the conventional vehicle design approach, the design of the next generation of vehicles is typically based on the design of previous generations. As a result, the objectives at the vehicle level and subsystem level become more focused on improving existing solutions rather than developing new solutions. Moreover, if a new solution is implemented in the existing vehicle design, it could lead to under-utilisation of the subsystem and possibly adverse effects on other subsystems. This could be because the current vehicle design process is preconditioned to the existing solutions [7]. Thus, the conventional approach to developing vehicles is very restrictive to introducing significant technological changes, and as a result, does not lead to significant improvements.

To enable this improvement, it is important to influence the design in the early stages where there is freedom for making significant changes [11]. However, one of the biggest challenges in influencing design in early-stage vehicle design is the lack of knowledge. This can be attributed to a design problem commonly referred to as the design paradox [8]. In the early stages of vehicle design, there is a lack of knowledge about the influence of transport-level design requirements over the design choices at the vehicle level and subsystem level, the resulting knock-on effects between the subsystems, and the overall performance of the vehicle. This lack of knowledge results in a sub-optimal vehicle design with increased design iterations.

Thus, to mitigate these drawbacks of the conventional approach, a cross-scalar design tool consisting of an induction motor model is presented in this paper. The tool calculates the motor's physical attributes (volume and mass), performance attributes (rated torque, maximum torque, and maximum power), and performance characteristics (torque-speed curve) to satisfy a given drive cycle's requirements. The tool achieves this by breaking down transport-level requirements into design requirements at the vehicle level and then further down to motor-level

10.1016/j.procir.2023.02.193

design requirements. However, unlike the conventional design approach, this design tool does not consider these subsystem-level design requirements as independent, but as a complex network of trade-offs.

This is achieved by developing the design tool as functional blocks where each block is a nested subsystem of the vehicle system. The design requirements of each block come from another block in the network. Thus, any changes made in one block affect the consequent blocks. This arrangement can also be imagined as a network, where each node is a vehicle's subsystem or component and the edges connecting the nodes are the design requirements passing from one node to the other. Thus, the design tool enables a holistic analysis of the influence of design requirements at the transport level on the design of the vehicle's subsystems and the consequent interaction effects among the subsystems and on the vehicle's overall performance. This analysis further helps the designer to develop efficient vehicles with minimised design iterations.

Nomenclature

a_i	Acceleration at specified position (m/s^2)
D_r	Rotor diameter (m)
f	Supply frequency (Hz)
F_{t_i}	Required tractive force at specified position (kN)
k_e	Eddy current loss coefficient
k_h	Hysteresis loss coefficient
k_ρ	Windage and bearing losses coefficient (Ws^2/m^4)
i	Gear ratio
I_S	Stator current (A)
I_r'	Rotor current (A)
l	Length of the motor (m)
m	Mass of the vehicle (kg)
m_{eq}	Equivalent mass of the train (kg)
m_l	Load on train (passengers and/or cargo) (kg)
m_p	Number of phases
n_m	Speed of the motor (rpm)
n_r	Speed of the rotor (rpm)
n_{base}	Base speed of the motor (rpm)
n_{rated}	Required rated speed of the motor (rpm)
p	Number of pole pairs
P_{rated}	Required rated power (kW)
P_{t_i}	Required tractive power at specified position (kW)
R_r'	Rotor resistance (Ω)
R_S	Stator resistance (Ω)
r_w	Radius of the wheel (m)
U_L	Line-to-line voltage (V)
v_i	Velocity of the vehicle at specified position (m/s)
v_r	Surface speed of the rotor (m/s)
$cos\phi$	Power factor
κ	Relative mass addition
τ_p	Stator pole pitch (m)

In this paper, the design tool is illustrated using conceptual rail vehicles as an example and the paper is organised as follows. In Section 2, the method followed to convert the drive cycle information into motor-level information is explained in two significant steps. These steps include the methods followed to derive the motor input parameters, power losses, and the torque-speed curve. In Section 3, the results obtained from the model, validation of the results, and the manner in which the results can be utilised to make design choices for other subsystems are briefly explained. In Section 4, the current limitations and possible future capabilities of the design tool are introduced. Finally, a summary and conclusions are provided in Section 5.

2. Method

In this section, the two major operations performed by the design tool are presented as two steps. In the first step, the method followed to convert the conventional drive cycle information into motor input parameters is explained. The drive cycle usually contains information about the distance, velocity, and relative track elevation. The motor input parameters are required rated power and rated speed. In the second step, the method followed to convert the motor input parameters to the motor's physical and performance attributes is explained. The motor's physical attributes are its volume and mass, and the performance attributes are rated torque, maximum torque, and maximum power. The overall procedure of the design tool is presented as a flowchart in Figure 1.

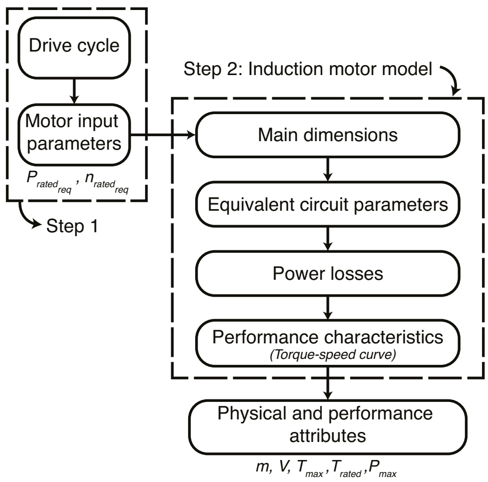

Fig. 1. Flowchart representing the steps involved in the design tool development

2.1. Step 1: Drive cycle information to Motor-level parameters

The objective of this step is to calculate the input parameters to the motor model from the drive cycle information. The input parameters are the required rated power and the required rated speed. Rated power is the maximum power with which the motor may run continuously over a long period of time and rated speed is the speed at which the maximum power occurs. The relationship between power and speed for a vehicle using electric motors for traction is depicted in Figure 2. The region in which the power increases is called the constant force/constant torque region. It increases up to a speed called the base speed. The base speed corresponds to the rated speed for the motor model in this paper. After the base speed, the power remains constant, and this region is called the constant power region.

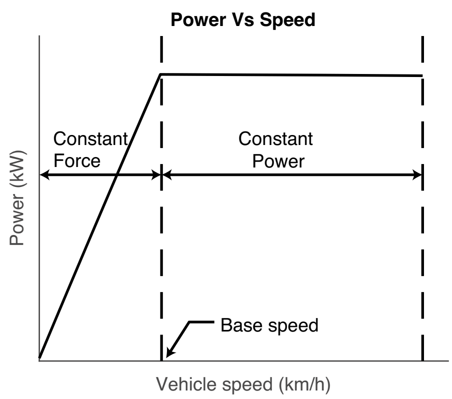

Fig. 2. Power and speed relationship of vehicle using electric traction motors

The drive cycle consists of information about the elevation of the track with respect to the start position and the velocity of the vehicle at every sampled position of the chosen route. A typical representation of a rail vehicle's drive cycle is presented in Figure 3. From this information, the motor input parameters are determined using the Newtonian equations of motion [1]. The required tractive power P_{t_i} at every position along the track is calculated using Equation 1. The required tractive force F_{t_i} is calculated using Equation 2. The acceleration of the vehicle a_i at every sampled position of the track is calculated using Equation 3. The equivalent mass of the vehicle m_{eq} is calculated using Equation 4.

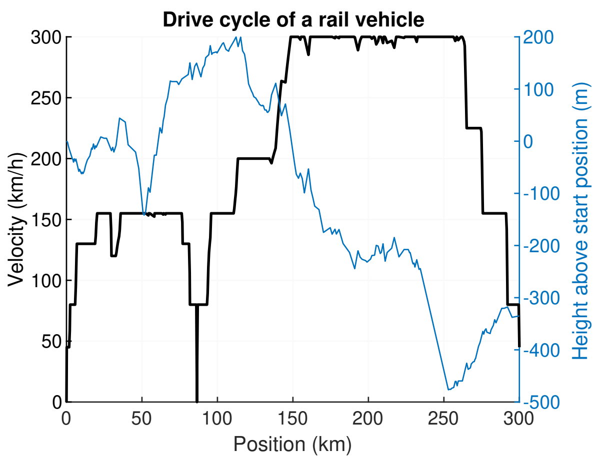

Fig. 3. Representation of typical drive cycle of a train

$$P_{t_i} = F_{t_i} v_i \quad (1)$$

$$F_{t_i} = m_{eq} a_i \quad (2)$$

$$a_i = \frac{v_i^2 - v_{i-1}^2}{2\Delta x} \quad (3)$$

$$m_{eq} = (m\kappa) + m_l \quad (4)$$

Equations 1 to 4 can be used to estimate the required tractive power at every sampled position of the track. However, to obtain more accurate information about the required power, different factors need to be taken into account, such as the different resistances experienced by the vehicle (viz., the aerodynamic resistance, curving resistance, gradient resistance, and rolling resistance), the maximum available adhesion, and the corresponding available traction force at every position of the track. The current design tool considers all these factors and calculates the required power at every position of the track and the result is displayed in Figure 4. It can be noted that it is similar to the relationship presented in Figure 2. However, the calculated power is the power required for the entire vehicle. To determine the power required per motor, the power is divided by the number of motors in the vehicle. Thus, the rated power per motor is calculated. The rated speed is calculated by identifying the speed at which the maximum power occurs. The vehicle speed is translated into motor speed using Equation 5.

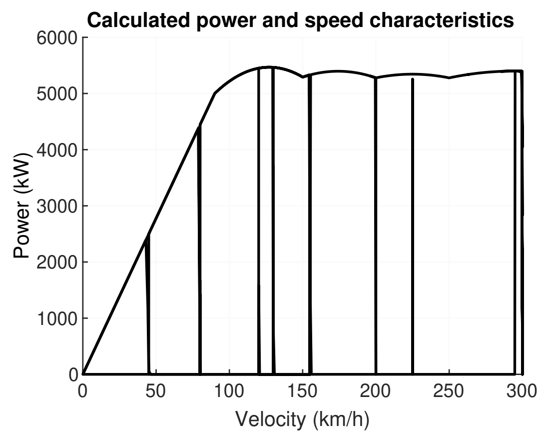

Fig. 4. Calculated power-speed characteristics of the high-speed rail drive cycle

$$n_m = \frac{v30i}{3.6\pi r_w} \quad (5)$$

2.2. Step 2: Induction motor model

The objective of this step is to develop an induction motor model that calculates the motor's physical attributes, performance attributes, and performance characteristics that satisfy the power and speed requirements obtained from the drive cycle. The design procedure followed is inspired by the versions presented in [2, 9]. The major steps involved to develop such a motor model are represented as a flowchart in Figure 1.

Initially, the input parameters are used to calculate the main dimensions of the motor such as its diameter, length, volume, and air-gap between the stator and the rotor. Some assumptions are made about the geometrical, electrical, and magnetic parameters of the motor to perform this calculation. The main dimensions are then used to calculate the equivalent circuit parameters such as the resistance, current, reactance, and impedance of both the stator and rotor. These parameters are vital as they are used to calculate the different power losses experienced by the motor. The power loss calculation is an important step in developing the induction motor model since they are used to calculate the performance characteristics of the motor such as the torque-speed curve.

An electric motor is a device that converts electrical energy into mechanical energy. During this conversion, the motor will experience different power losses which occur in the form of heat at different stages of this conversion as depicted in Figure 5.

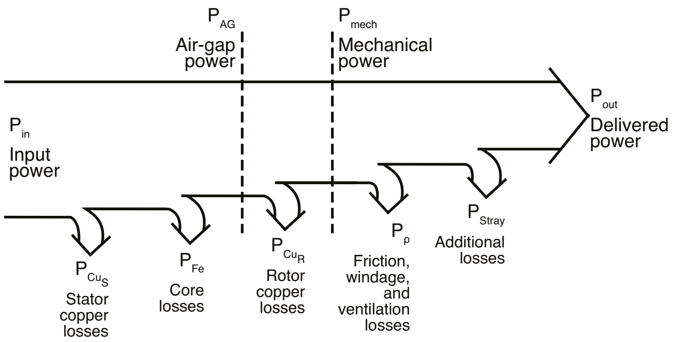

Fig. 5. Power-flow diagram of induction motor

The power delivered at the motor shaft and the corresponding torque are calculated using Equation 6 and Equation 7 respectively. The electrical input power to an induction motor is calculated using Equation 8. The supplied current flows through the stator windings and causes the stator copper losses (P_{Cu_S}). The stator copper losses constitute the majority of losses and are calculated using Equation 9. The stator current causes a rotating magnetic field which leads to eddy current and hysteresis losses which are commonly referred to as core or iron losses. The core losses are a function of the frequency, the magnetising flux, the material being utilised in the motor, and also the equivalent circuit parameters of the motor. An approximation of the core or iron losses is calculated using Equation 10. The remaining power is then transferred to the rotor across the air-gap and referred to as the air-gap power (P_{AG}). The transferred power causes a torque in the rotor and thus the rotor rotates, and at this stage, the rotor experiences copper losses. These are called rotor copper losses (P_{Cu_R}) and are calculated using Equation 11. The remaining power is converted to mechanical energy (P_{mech}). In addition to the electrical and magnetic losses, the motor experiences mechanical losses such as friction, windage, and ventilation losses (P_ρ) and are calculated using Equation 12. In some cases, there are some unaccounted losses called stray losses (P_{stray}). These losses are not considered in this paper. The equations are derived from [2, 3, 9] for calculating the various power losses, input and output power, and the torque developed.

$$P_{out} = P_{in} - P_{Cu_S} - P_{Fe} - P_{Cu_R} - P_\rho \tag{6}$$

$$T_{out} = \frac{P_{out}60}{2\pi n_r} \tag{7}$$

$$P_{in} = \sqrt{3} U_L I_s \cos\phi \tag{8}$$

$$P_{Cu_S} = m_p I_s^2 R_s \tag{9}$$

$$P_{Fe} = k_h f \Phi_m^2 + k_e f^2 \Phi_m^2 \tag{10}$$

$$P_{Cu_R} = m_p I_r'^2 R_r' \tag{11}$$

$$P_\rho = k_\rho D_r (l_r + 0.6\tau_p) v_r^2 \tag{12}$$

$$n_{base} = \frac{60f}{p} \tag{13}$$

This design, however, is for one specific frequency of the motor. This frequency is known as the base supply frequency and it corresponds to the base speed of the motor as explained through Equation 13. To develop the torque-speed curve of the motor across its entire operating range, a control logic known as Variable-Voltage-Variable-Frequency (VVVF) is implemented [2, 3, 4, 9]. The control logic regulates the voltage and the frequency supplied to the motor throughout the motor's entire operating range. Similar to the power, the input voltage is increasing until the base frequency, and it is constant after the base frequency. Thus, it facilitates a constant-torque region until the base frequency and a constant-power region after the base frequency.

3. Results and Discussion

The motor's physical and performance attributes calculated by the design tool, based on two different drive cycle requirements, namely the high-speed train and the metro, are tabulated in Table 1. The derived performance characteristics, namely the torque-speed curve is displayed in Figure 6. It can be noted that for the high-speed train in Table 1, in the first configuration, the maximum values of power and torque are almost twice their respective rated values. However, this is not the case in all situations. This ratio of maximum to rated values of power and torque can vary based on the type of the train [13], but they are largely dependent on the thermal capabilities of the traction system [1]. This includes the insulation, cooling method utilised, and the limit up to which the traction converters, inverters, and motor are allowed to overheat before they fail.

Since the input requirements were that the motor should be able to produce a power of 683 kW and a torque of 5.625 kNm continuously for longer operation times with the available thermal capabilities, the design tool produces an oversized motor design. In this design, the required power and torque are almost half the maximum power and torque of the motor. This way the motor always runs at a lower level than its maximum capability and thus does not overheat. However, these constraints and requirements lead to a heavier motor.

There are also other design parameters such as the frequency and the rated speed of the motor, which can influence the ratio without modifying the thermal capability of the motor. Keeping the other parameters constant, increasing the frequency and the rated speed of the motor has a negative effect on the output torque. Thus, for a given thermal capability of the motor, the frequency and the corresponding rated speed are increased such that the ratio is lower and the results are tabulated in Table 1 under configuration 2 of the high-speed train. In this case, it can be noted that there is a considerable difference in the physical attributes of the motor, especially the mass of the motor, which is almost half the mass value in configuration 1.

A similar analysis is performed using a drive cycle of a metro to test the robustness of the design tool and the results are tabulated in Table 1. However, in configuration 2 of the metro train in Table 1, it can be seen that there are no significant changes in the maximum power and maximum torque when compared with the results in configuration 1 of the metro train. This is because the frequency of configuration 2 is decreased compared to configuration 1, which would increase the maximum values. And the rated speed is increased compared to configuration 1, which would decrease the maximum values. Thus, the ratio can also be kept similar while altering the design parameters.

Thus, it is inferred that the design tool can be utilised to understand the influence of design requirements on the design parameters for the motor, and consequently the manner in which these identified parameters influence the different attributes of the motor and in turn the performance of the vehicle. This would thus help a designer to understand the consequences of different choices and help design a vehicle/subsystem based on the requirements.

Table 1. Results obtained from the design tool for different configurations of high-speed and metro train drive cycles

	Attribute	**Configuration 1**	**Configuration 2**
High Speed Train	Frequency (Hz)	37	50
	Rated speed (rpm)	1061	2000
	Rated Torque (kN)	5.625	5.625
	Maximum Torque (kN)	10.317	5.812
	Rated Power (kW)	683.00	683.00
	Maximum Power (kW)	1163.752	839.105
	Volume of the motor (m^3)	0.560	0.303
	Mass of the motor (kg)	3660.564	1906.181
Metro Train	Frequency (Hz)	60	50
	Rated speed (rpm)	1836	2000
	Rated Torque (kN)	1.264	1.264
	Maximum Torque (kN)	2.292	2.123
	Rated Power (kW)	250	250
	Maximum Power (kW)	418.762	323.751
	Volume of the motor (m^3)	0.125	0.115
	Mass of the motor (kg)	757.923	691.951

Furthermore, an analysis is performed using the design tool to understand the influence of different design variables on a specific objective function. The influence of varying different design variables such as the air-gap of the motor (g), the number of stator turns (N_s), the length of the motor (L), and the resistance of the rotor (R_r) on the output torque (T) is analysed and the results are depicted in Figure 7. The behaviour obtained from this analysis is similar to the results presented in

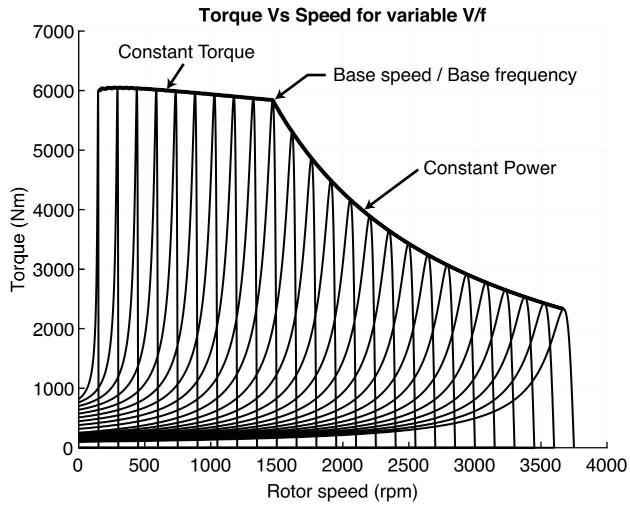

Fig. 6. Torque-speed characteristics obtained from design tool for high-speed train drive cycle

[6, 10] and thus further helps in validating the results obtained from the design tool. This information could help the designer to understand which design variables to modify to influence the objective function as required.

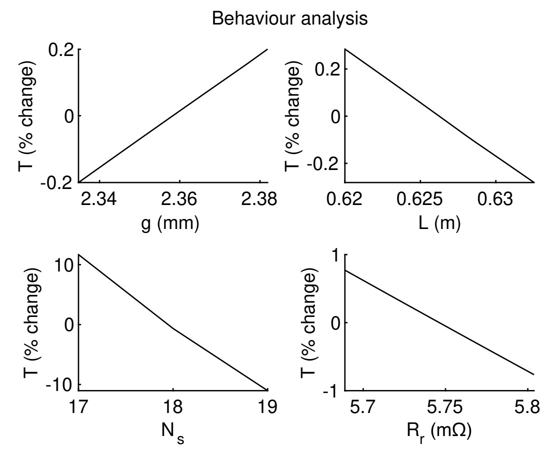

Fig. 7. Torque behaviour with respect to variation in different design parameters

4. Future work

The design tool is developed in a detailed manner to make it robust. However, the extensive nature of the design tool results in an increased number of parameters that need to be assumed. This can lead to a situation where a desired property cannot be controlled. For example, it would be beneficial to control the ratio of maximum to rated values of power and torque. However, it cannot be controlled since it is a consequence of the interaction between various parameters. Therefore, an extensive uncertainty and sensitivity analysis shall be performed. This will help in identifying the influential parameters and understanding the relationship between the influential parameters and the desired output and in turn help in controlling the design tool.

Moreover, to extend the capabilities of the design tool, other subsystems have to be developed and integrated into the design tool. This would help in performing the subsystem interaction analysis.

For example, the influence of motor design on braking system design can be analysed. The braking system in rail vehicles consists of mechanical brakes (disc brakes) and regenerative brakes (the direction of traction motors is reversed to produce braking force). The mechanical brakes design depends on the required brake force and thermal capabilities [5]. And the mechanical brakes are utilised only when the regenerative brakes are insufficient. Thus, if the traction motor is designed such that sufficient braking force is provided, and if regenerative capabilities can be utilised to their maximum, the utilisation of mechanical brakes could be limited. This would mean the number of brake discs required, the brake wear, and the energy consumption can be improved by improving the design of regenerative braking and mechanical braking systems [12]. This analysis shall be performed in the future by developing the braking system and integrating it into the design tool.

Furthermore, the gear ratio and the wheel diameter are important design parameters which can influence the maximum torque, maximum power per motor and number of motors required. Therefore, the influence of gear ratio and wheel diameter on the required number of traction motors, the required number of powered axles for a vehicle, and the corresponding axle loads shall be analysed.

5. Summary and Conclusion

In this paper, a design tool consisting of an induction motor model that translates the drive cycle requirements to motor attributes has been presented. The two major operations performed by the design tool have been presented as two steps. In the first step, the method to translate the drive cycle information to motor input parameters has been explained. In the second step, the method to calculate the motor's physical and performance attributes from the motor parameters has been explained. The analysis performed with different drive cycles and motor configurations indicated that the design tool is capable of influencing the motor design based on the drive cycle requirements. Furthermore, the behavioural analysis performed indicated that the design tool is able to influence the motor attributes by varying different design parameters. The results obtained from the behaviour analysis are similar to the results presented in previous research works. This helps in validating the methodology of the design tool. Although the design tool is developed to be robust, there are certain limitations which need to be addressed in the future. An extensive uncertainty and sensitivity analysis shall be performed to understand the relationship between different design parameters and the desired output. Other subsystems and components of the vehicle (the braking system, the gearbox, and the wheels) shall be integrated into the design tool to extend the capabilities of the design tool. This would enable the design tool to analyse the influence of design requirements on the design of different subsystems and the interaction effects among the subsystem's design and performance parameters. This shall further help in developing efficient vehicles with minimised design iterations.

Acknowledgements

The authors would like to thank the Centre for ECO^2 Vehicle Design, which is funded by the Swedish Innovation Agency Vinnova (Grant Number 2016-05195) and the strategic research area TRENoP for their financial contributions to this work.

References

[1] Andersson, E., Berg, M., Stichel, S., Casanueva, C., 2016. Rail Systems and Rail Vehicles : Part 2: Rail Vehicles. 1 ed., KTH Royal Institute of Technology, Stockholm.

[2] Boldea, I., Nasar, S.A., 2010. The induction machines design handbook. The electric power engineering series. 2nd ed., CRC Press/Taylor & Francis, Boca Raton, FL. doi:https://doi.org/10.1016/B978-075065092-2/50003-1.

[3] Chapman, S.J., 2005. Electric machinery fundamentals. 4th ed ed., McGraw-Hill Higher Education, New York, NY.

[4] Ghosh, S., Gupta, A., Dashora, H., Ranjan, S., 2020. Mathematical Approach to Generate Efficiency Maps for Induction Motor and Optimization for EV, in: 2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC), IEEE, Nagpur, India. pp. 1–6. doi:10.1109/STPEC49749.2020.9297758.

[5] Günay, M., Korkmaz, M.E., Özmen, R., 2020. An investigation on braking systems used in railway vehicles. Engineering Science and Technology, an International Journal 23, 421–431. doi:10.1016/j.jestch.2020.01.009.

[6] Haghighian, R., Mazinanian, M.R., Vahedi, A., 2016. Sensitivity analysis to improve the design process of an induction motor using MEC, in: 2016 7th Power Electronics and Drive Systems Technologies Conference (PEDSTC), IEEE, Tehran, Iran. pp. 35–40. doi:10.1109/PEDSTC.2016.7556834.

[7] Hodkinson, R., Fenton, J., 2000. Introduction, in: Hodkinson, R., Fenton, J. (Eds.), Lightweight Electric/Hybrid Vehicle Design. Butterworth-Heinemann, Oxford. Automotive Engineering Series, pp. xi–xxx. doi:https://doi.org/10.1016/B978-075065092-2/50003-1.

[8] O'Reilly, C.J., Göransson, P., Funazaki, A., Suzuki, T., Edlund, S., Gunnarsson, C., Lundow, J.O., Cerin, P., Cameron, C.J., Wennhage, P., Potting, J., 2016. Life cycle energy optimisation: A proposed methodology for integrating environmental considerations early in the vehicle engineering design process. Journal of Cleaner Production 135, 750–759. doi:10.1016/j.jclepro.2016.06.163.

[9] Pyrhonen, J., Jokinen, T., Hrabovcová, V., 2014. Design of rotating electrical machines. Second edition ed., Wiley, Chichester, West Sussex, United Kingdom.

[10] Rajinder, Sreejeth, M., Singh, M., 2016. Sensitivity analysis of induction motor performance variables, in: 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), IEEE, Delhi, India. pp. 1–6. doi:10.1109/ICPEICES.2016.7853609.

[11] Schöggl, J.P., Baumgartner, R.J., Hofer, D., 2017. Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry. Journal of Cleaner Production 140, 1602 – 1617. doi:10.1016/j.jclepro.2016.09.195.

[12] Sjöholm, M., 2011. Benefits of regenerative braking and eco driving for high-speed trains : Energy consumption and brake wear. Student thesis. URL: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-31701. iSBN: 16517660 (ISSN).

[13] Östlund, S., 2012. Electric Railway Traction. 10 ed., KTH Royal Institute of Technology, Stockholm.