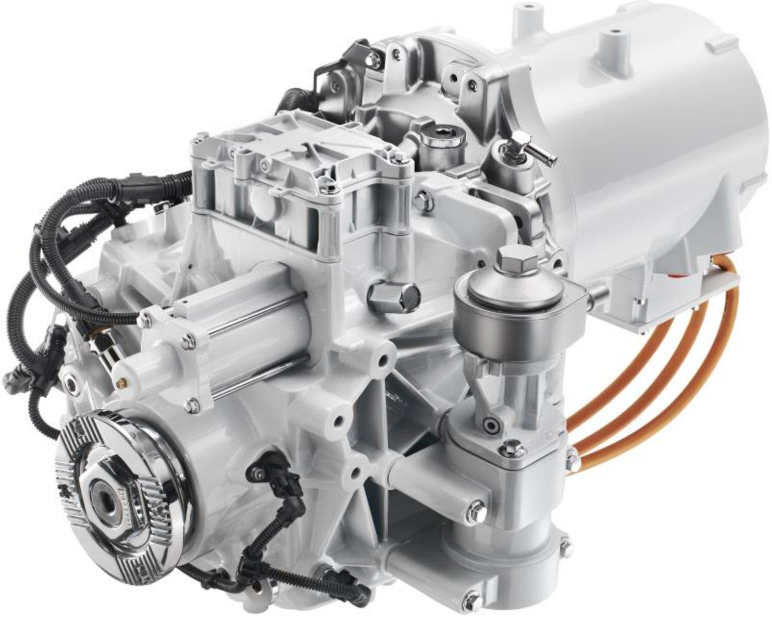

# Improve Testing and Model Verification of Electric Drive Systems

## Electric drive systems in hybrid vehicles

Master's thesis in Systems, Control and Mechatronics

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# Improve Testing and Model Verification of Electric Drive Systems

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Cover picture: Volvo Group AB, ”Electric powertrain”

# Abstract

Hybrid powertrains have several advantages over conventional powertrains, such as reduced fuel consumption. However, they are more complex and so are also the models of such systems. This master's thesis purpose is to partially answer the two research questions: How accurate can electric Drive System (DS) models output be correlated with measured data? How do changes of inputs affect a DS model output?

To contribute to answers, two models of drive systems, DS1 and DS2, are verified by tests, and a sensitivity analysis is performed on DS1. The models are tested in a virtual testbed that imitates hardware tests. Both DS1 and DS2 are 48V systems that consist of a controller, an inverter and a Permanent Magnet Synchronous Machine (PMSM). The model of DS1 is supplied by Renault Trucks, while the model of DS2 is selected using a product development procedure described in the book *the value model*. A specification of requirements is established, including accuracy requirements. It is used to develop test and verification procedures. The tests are, when possible, performed according to an internal norm at Renault Trucks. In calculations are DS ratings used, so that the reader can use his own data.

A verification of DS1 max torque and power using test data and model simulation shows a deviation of $-3\%$ to $6{,}5\%$. Data from the same verification shows an efficiency deviation of $-0{,}9\%$ to $1{,}3\%$. The same verification procedure on DS2 shows a deviation of $5{,}1\%$ to $33\%$ in max torque and power and $-19\%$ to $5{,}1\%$ in efficiency. The DS1 model has power losses at zero torque demand of 0,7% at 3500 rpm and 5.5% at 9000 rpm of DS1 rated power in simulation. The DS2 model has power losses at zero torque demand of 0,1% at 230 rpm and 5% at 14100 rpm of DS2 rated power in simulation. The DS1 model has a derating time from peak to nominal power of 1450 seconds at 3500 rpm and 1273 seconds at 9000 rpm in simulation. Parameters to populate the DS2 model's derating function are not available, thus the DS2 model has no deratings. An ideal cooling system model is used in the simulations.

A sensitivity analysis in simulation is performed on the DS1 model. An expected nominal voltage deviation of $\pm 2V$, at 6000 rpm, makes the torque output deviate from its nominal value with $4{,}8\%$ and $-7\%$, respectively. An increment of the cooling water temperature of 10°C from 65°C, at 6000 rpm, makes the torque output deviate from its nominal value with $-2\%$. A second increment gives a deviation of $-4\%$.

The DS1 model has a deviation of $\leq 10\%$. The model is accurate enough to be used in simulations of hybrid powertrains, even if more testing is recommended to be able to better assess results from such simulations. More data and tuning of the DS2 model are required to reduce its verification deviation to $\leq 10\%$.

**Keywords** : Power electronics; Modelling and simulation; PMSM; Sensitivity analysis; IVAR project; Test; Verification.

# Résumé

Les groupes motopropulseurs hybrides présentent plusieurs avantages par rapport aux groupes motopropulseurs conventionnels, tels que la réduction de la consommation de carburant, mais ils sont plus complexes de même que les modèles de tels systèmes. Le but de ce rapport de stage est de répondre en partie à deux questions de recherche: Quel degré de corrélation peut être atteint entre un modèle et des mesures d'essais? Comment l'incertitude de la sortie d'un système peut-elle être attribuée à l'incertitude de ses entrées?

Pour contribuer à apporter des réponses, deux modèles de systèmes de propulsion électrique, DS1 et DS2, sont vérifiés par des essais, et une analyse de sensibilité est effectuée sur DS1. Les modèles sont testés sur un banc d'essai virtuel, qui imite les tests effectués sur le banc d'essai réel. Les systèmes DS1 et DS2 sont de 48V et se composent d'un onduleur, d'un contrôleur et d'une machine synchrone à aimants permanents (PMSM). Le modèle de DS1 est fourni par Renault Trucks et le projet sélectionne le modèle de DS2 selon un procédé décrit dans le livre *the value model*. Un cahier des charges détaillé est établi pour les essais et la vérification. Il contient des exigences de précision. Les essais suivent une norme interne à Renault Trucks quand c'est possible. Des indices des DS sont utilisés pour les calculs, le lecteur peut donc utiliser ses propres données.

Une vérification du couple et puissance maximal de DS1 utilisant des données de test et de modèle simulation montre un écart de $-1{,}3\%$ à 6,5%. La même vérification pour l'efficacité montre un écart de $-0{,}9\%$ à 1,3%. La même procédure de vérification pour DS2 montre un écart de 5,1% à 33% sur la puissance et le couple max et $-19\%$ à 5,1% sur l'efficacité. Le modèle DS1 a une perte de puissance de 0,7% à 3500 tr/min et 5,5% à 9000 tr/min par rapport à la puissance nominale, pour une demande de couple nul en simulation. Le modèle DS2 a une perte de 0,1% à 230 tr/min et 5% à 14100 tr/min de puissance nominale pour une demande de couple nul en simulation. Le modèle DS1 donne un temps de détarage de la puissance maximale à la puissance nominale de 1450 secondes à 3500 tr/min et 1273 secondes à 9000 tr/min en simulation. Il n'y a pas des valeurs fournies pour mettre à jour les paramètres dans le modèle DS2 pour la perte de puissance, par conséquent le modèle DS2 ne donne pas de détarage en simulation. Un modèle idéal est utilisé pour le système de refroidissement en simulation.

Une analyse de sensibilité sur le DS1 modèle est réalisée en simulation. Un écart attendu de la tension nominale de $\pm 2V$ pour une puissance assignée à 6000 tr/min, fait dévier le couple de sortie de 4,8% respectivement de $-7\%$ de sa valeur nominale. Une augmentation de la température de l'eau refroidissement de 10°C à partir de 65°C, pour une puissance assignée à 6000 tr/min, fait dévier le couple de sortie de $-2\%$. Une deuxième augmentation donne un écart de $-4\%$.

Le modèle DS1 a une déviation $\leq 10\%$, il est suffisamment précis pour être utilisés dans des simulations de groupes motopropulseurs hybrides, même si des tests supplémentaires sont recommandés pour mieux comprendre les résultats des simulations. Plus de données et une mise à jour du modèle DS2 est nécessaire pour réduire la déviation de la vérification à $\leq 10\%$.

**Mots-clés** : Électronique de puissance; Modélisation et simulation; Machine synchrone; Analyse de sensibilité; IVAR projet; Test; Vérification.

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Ted Eriksson, Gothenburg, October 2020

*Contributions*
Andersson Rasmus – Electric machine design.
Andersson Rickard – Simulation.
Bland David – Tests and measurements.
Boëte Yann – Verification processes.
Colliot Caroline – Verification process.
Hellal Benzaoui – Mathematical discussions.
Nyberg Marcus – Tests.
Morge Fabien – Tests.
Xavier Huin – His thesis has inspired the structure in some chapters.

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# Acronyms

| | |
|---|---|
| BLF | Binary Log File |
| BSG | Belt Starter Generator |
| CAN | Controller Area Network |
| CAD | Computer Aided Design |
| CG | Chalmers General. Model described in the Chalmers course ENM076 |
| DS | Drive System |
| EA | Electric Axel |
| ECU | Electronic Control Unit |
| EM | Electric Machine |
| ESAM | External Starter Alternator Motor |
| EV | Electric Vehicle |
| FIR F | Finite Impulse Response Filter |
| FOC | Field Oriented Control |
| GSP | Global Simulation Platform |
| ICE | Internal Combustion Engine |
| INV | Inverter |
| ISAM | Internal Starter Alternator Motor |
| ISG | Internal Starter Generator |
| LEZ | Low Emission Zone |
| MG | Motor/generator |
| MTPA | Max Torque Per Ampere |
| OP | Operation Point, see PV |
| pu. | Per-unit |
| PV | Process Variable, measurement |
| Radv | Renault Advanced |
| Rstd | Renault Standard |
| SMC | Simscape Motor Control |
| SP | Set Point |
| SS | Steady State |
| ZEV | Zero Emission Vehicle |
| ZEZ | Zero Emission Zone |

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# 1 Introduction

The first part of this chapter gives a background to why verification by test and simulation results analysis are relevant when including electric drive systems in a powertrain. Then are purpose and aims of this thesis stated. A scope of the project is presented to clarify the aims.

## 1.1 Background

Strict requirements to reduce emissions from vehicles are driving Original Equipment Manufacturers (OEM's) to focus on electrification of powertrains as a possible solution [1]. Electric powertrains have been manufactured in Europe since the '80s, but the range of applications has been limited by battery capacities. Recent battery advancements can make electric and hybrid powertrains a suitable solution in trucks to reduce emissions [2].

An addition of an electric motor Drive System (DS) to a powertrain with an Internal Combustion Engine (ICE) increases the powertrain complexity and makes it harder to evaluate its abilities. Renault Trucks evaluates powertrains with DS, and they put effort on modeling and simulation to secure fuel economy and emission reduction in an early project phase. Their evaluations are based on that actual events and processes are reproduced with some accuracy in their simulations. Thus, there is a need to verify their DS models, so they meet technical standards, which include accuracy requirements. Documentation from the verification is required to enable traceability of undesired behaviors in their simulations [3]. An accurate model of a powertrain is of importance, but an accurate model can add undesired complexity that results in heavy simulations and time-consuming testing.

A conventional powertrain consists of an ICE, a transmission, a drive shaft and a differential, while an electrified hybrid powertrain in addition has a DS consisting of an inverter, a controller and an electric machine [2]. DS that have a Permanent Magnet Synchronous Machine (PMSM) are often evaluated since they have high power density, thus they leave more volume for cargo than other machine options [4].

## 1.2 Purpose and aims

The aims of this project are to use two electric Drive Systems, DS1 and DS2, with corresponding datasets to:

- Verify and perform a sensitivity analysis on an existing model of DS1.
- Develop and verify a model of DS2.

Renault Trucks intend to use these models to evaluate fuel economy and emissions.

The purpose of this thesis is to partially answer the following research questions:

- How accurate can a model's output be fit onto measured data?
- How do changes of inputs affect a model's output?

## 1.3 Scope

Four DS consisting of an inverter, a controller and a PMSM are considered in this project, which are presented in Figure 1. DS1 and DS2 are studied in this report. A drive system called DS1x, is used to evaluate verification processes. Another drive system called DS2x can, due to its similar design to DS2 be used to generalize the model of DS2. The DS are intended to be used in an ExSAM P3 powertrain architecture, as defined in chapter 2. Renault Trucks has chosen to evaluate this powertrain architecture, but they also evaluate other architectures. Since the report is intended to work as a guide, DS parameters are stated in terms of machine ratings.

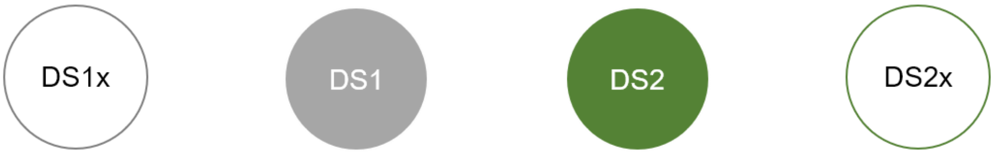


*Figure 1 Drive systems considered in this project.*

Project limitations:

- No other software supplier than MathWorks, to ensure software modularity.
- No other machine type than PMSM is considered, due to power density requirements.
- Not all machine modes are evaluated.
- No results are presented for other DS than DS1 and DS2.
- No change is made in the DS1 model.
- No use of other data than from suppliers, testbed, dynamometer and a specified vehicle.
- No economic calculations, all equipment is provided by Renault Trucks.
- No changes to the DS hardware are considered, since no DS design is performed.

The main consequence is that only DS with PMSM are considered in this project.

## 1.4 Deliverables

Interviews with the project's players and stakeholders identify following deliverables:

- A model of DS2.
- A test and a verification procedure for DS1 and DS2.
- Results from DS1 and DS2 model verifications and simulations.

## 1.5 Project work model

This project is realized by using outlines from the Value model that is a project work model defined in the book *the Value model – How to Master Product Development and Create Unrivalled Customer value* [5] . The aim of using this work method is to create academic and industrial value.

A project according to the value model is initialized by a *proposal* and a *project definition* comprising of:

- A definition of the most important players and stakeholders.
- A verbal formulation of project aims.
- A definition of the different project segments.
- A list of the most important deliverables.
- A scope.
- Sponsors approval of the project.

Functions are then described to create a *specification of requirements*. A *concept generation* and a *concept selection* are performed. To find the most suitable concept, solution alternatives are processed through an elimination process, consisting of elimination matrices. If several concepts pass the elimination, the best concept can be selected by using Pugh's method. The most suitable solution is implemented and verified. The project results are presented in a structured *report* and in a *presentation*.

# 2 Electrical drive systems for trucks

In this chapter the background is expanded, electric vehicles are categorized, and hybrid powertrain architectures are presented. Truck ranges and conventional powertrains are covered in several medias, and they are therefore not discussed in this chapter. An example of an animation covering a modern conventional powertrain is V*olvo Trucks fuel saving powertrain* [6]. The product range of trucks can be studied by using truck companies' information, such as Renault Trucks information *Our trucks* [7]. In this thesis, a truck is any vehicle that can be driven by a driver with a Swedish C driving license.

Hybrid powertrains in trucks can reduce emissions to meet emission requirements and reduce fuel consumption, thus reducing operating costs. Examples of emission requirements are found in EURO VI regulations for heavy duty vehicles, which became mandatory on 1 January 2013. A development of a post-Euro VI emission standard for trucks is in progress [8] [9]. An electric DS can, depending on architecture, be used to meet new requirements by:

- *Regenerative braking*: a vehicle's kinetic energy is recovered and stored at braking. The energy can be used to drive the vehicle or its auxiliaries. It can also *reduce brake wear*.
- *Torque assist*: a DS can reduce the peak output required from the ICE. It implies that the ICE can be downsized. An optimization of the interaction between the DS and ICE can be performed to improve overall efficiency. The assist can also boost the vehicle when overtaking and improve a truck's gradeability.
- *Pure electric drive*: a truck using only a DS allows it to enter zero emission zones.

Cities around the world are working to solve major challenges of urbanization, such as air quality, noise and congestion [10]. A DS in a powertrain can improve a vehicles efficiency, thus reducing emissions and operating cost. Vehicles that comply with Low Emission Zones (LEZ) or Zero Emission Zones (ZEZ) regulations can solve some urbanization challenges by making the introduction of more of these zones realizable. A truck that is allowed into these zones creates value for the costumer. As of 2019, there are about 250 LEZ in EU which help meet EU health-based air quality limit values. An example is the LEZ in the town of Gothenburg as described in Figure 2 [11].

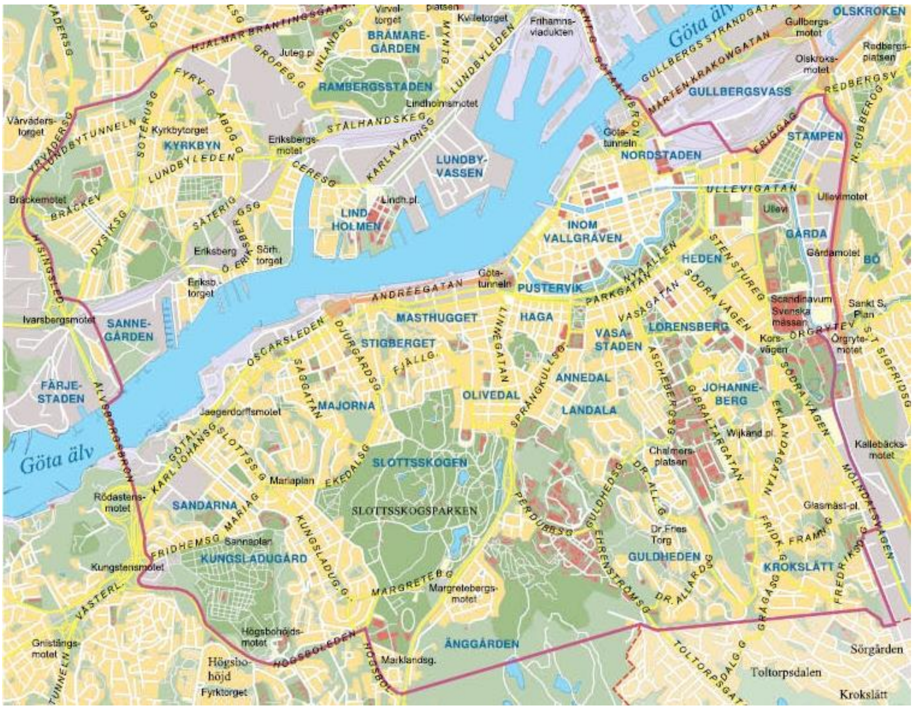


*Figure 2 Low emission zone in Gothenburg 2020.With courtesy of stadsbyggnadskontoret Göteborg* [12].

## 2.1 Classification and architectures

In this section electric hybrid vehicles are classified, and hybrid powertrain architectures are presented. Electrified vehicles (EV) are classified depending on functions accordingly to Table 1.

*Table 1 Classification of hybrid vehicles [13].*

| | | Start & stop | Hybrid type | | | Pure EV |
|---|---|---|---|---|---|---|
| | | | Micro | Mild | Full | |
| Function | Start & stop of ICE | X | X | X | X | - |
| | Regenerative braking | - | X | X | X | X |
| | Torque assist | - | - | X | X | X |
| | Pure electric take-off and drive | - | - | - | X | X |

The number and the position of DS in a hybrid powertrain define the architecture [14]. There are four main architectures:

- *Series*: an ICE drives an electric generator that produces electrical power. The power is then used to drive a motor that drives the wheels. A battery can be used as a buffer in the system.

- *Parallel:* an ICE and a DS drive the wheels via a mechanic connection that sums the torques mechanically, as presented in Figure 3.

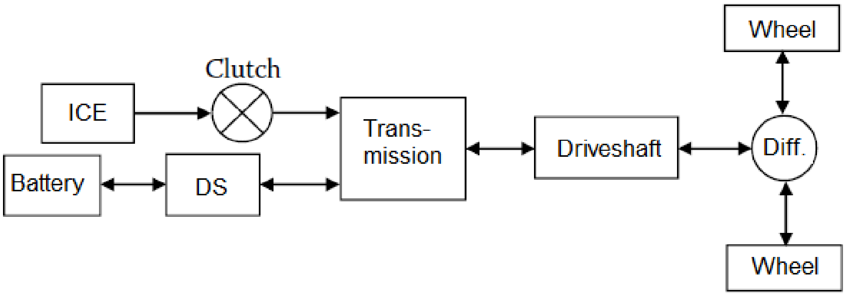


*Figure 3 A parallel architecture of a hybrid powertrain.*

- *Power split:* an ICE and two DS are connected to a power split device. This enables a combination of series and parallel operation. A physical model demonstration of the somewhat complex system can be found in Consulabs video *Hybrid planetary gearset trainer* [15].

- *Series/parallel:* two clutches that can engage or disengage the ICE and the DS allow to change the powertrain configuration from series to parallel and vice versa. Depending on operation conditions, the most suitable configuration can be selected.

Each architecture has advantages and disadvantages. The main advantage of the series architecture is that only electrical connections are required between the power conversion devices, which simplifies a vehicle's design. Furthermore, the system is mechanically disconnected from the wheels, thus load and speed can be chosen so the ICE can run at its optimal operation speed. At low speed, this usually makes the architecture more efficient than a powertrain with an ICE. Parallel architecture usually have smaller machines than series, thus the regenerative braking power is often lower than in series architectures, but the overall performance is better at high speed. Power split and series/parallel architectures have a flexibility that can improve overall efficiency, but they are more complex than series and parallel architectures [14].

### Parallel hybrid powertrains subcategories

In this section, subcategories of parallel hybrid powertrain architectures are described, as presented in Figure 4 [16]. The subcategories are defined by the DS position, as presented in Figure 5, and they are as follows:

- *Position 0 Belt Starter Generator*: the DS is mounted to the ICE on the opposite side of the transmission. The main advantage of this placement is that the DS can replace a start motor and an generator. The DS can be used for regenerative braking. A drawback of this placement is the low efficiency if the DS is used to drive the vehicle.

- *Position 1 Integrated Starter Generator:* the DS is mounted to the ICE crankshaft and it can be used for regenerative braking and to start the ICE. The main advantage of this DS placement is that it can be made compact. The main drawback is that it is not as efficient as a DS that can be decoupled from the ICE.

- *Position 2 Integrated Starter Alternator Motor:* the ICE and the DS are placed on opposite sides of the clutch. The DS can be used for regenerative braking. The main advantage of this DS placement is that the vehicle can drive in pure electric mode, without ICE drag torque losses. The main disadvantage of this DS placement is the limitation of space at this position.

- *Position 3 External Starter Alternator Motor*: The DS is connected to the gearbox. The DS can be used for regenerative braking and can also be used to charge the batteries while the vehicle is standing still if the gears are put in neutral. The main advantage of placing a DS at this position is that it can be used without ICE drag torque losses and with low torque losses in the gearbox. The main disadvantage of this DS placement is that a more powerful DS is required than at position 1 and 2 if it should be used to start the ICE.

- *Position 4 Electric Axel*: The DS is connected to the differential or the tires. The main advantage of placing a DS at this position is high efficiency due to low transfer losses. The DS can be used for regenerative braking. The main drawback of the placement is that the DS cannot be used as a generator to charge the batteries while the vehicle is standing still.

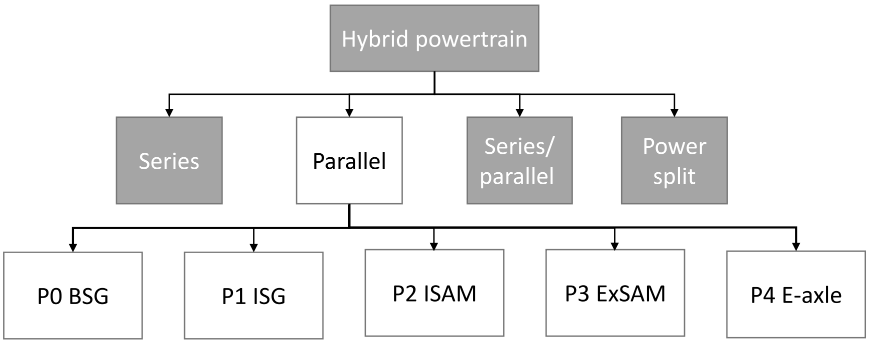


*Figure 4 Subcategories of parallel hybrid powertrain architectures.*

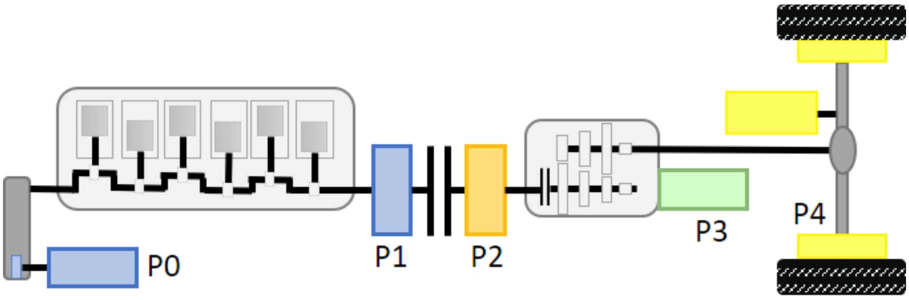


*Figure 5 Potential DS Positions 1-4 in a parallel hybrid powertrain architecture [13].*

# 3 Criteria DS2 model

In this chapter, the project is clarified by creating a specification of requirements for the DS2 model. Criteria for the verification procedure are found in chapter 7. The final specification of requirements is presented in Annex I.

## 3.1 Functions

In this section, the functions of the DS2 model are stated.

### Required functions

The DS2 model inputs and Required and Desired outputs are specified in Table 2.

*Table 2 DS2 model inputs and required and desired outputs.*

| Inputs | | Outputs | | R/D |
|---|---|---|---|---|
| Torque demand | [Nm] | Torque | $[Nm]$ | R |
| DC source voltage | $[V]$ | Simulation time | $[sec]$ | R |
| Water flow | [l/min] | Supply current | $[A]$ | R |
| Angular velocity | $[rad/s]$ | Winding temperature | [°C] | R |
| EM water inlet temperature | [°C] | Heat sink temperature | [°C] | D |
| | | Motor loss | $[W]$ | D |
| | | Inverter loss | $[W]$ | D |
| | | Transistor Temp | [°C] | D |
| | | Id | $[A]$ | D |
| | | Iq | $[A]$ | D |
| | | Machine voltage | $[V]$ | D |
| | | Water outlet temperature | [°C] | D |
| | | Delta water pressure | [Pa] | D |

- Accuracy deviation from actual events $\leq 10\ \%$

During simulation errors accumulate, thus an accurate model contributes less to a global error when several models are simulated. The model cannot be used in all intended simulations if the model output deviates from actual events with more than 10%, as described in chapter 6.

- Stability

A crash during a simulation of a model costs time and makes it difficult to build upon the model. The model is required to run without errors.

- Performance

A simulation of the model should not be too heavy to calculate, since this will increase the simulation time, which is a considerable obstacle for the user. A model simulation of the DS2 model shall not exceed 150% of the average Renault advanced DS model simulation time, using the same hardware.

- Modularity

It should be possible to divide the model into a controller and a machine module. These software modules can then be reused in other projects.

- Supplier compliance and data

The model must be possible to implement using only measured data or information that can be acquired within any contracts with suppliers.

- Model support and adaption

Renault is required to have staff that can support a user of the model and be able to continually adapt the model.

**Desired functions**

Desired functions add value but are not required. Desired model outputs are found in Table 2.

- Automatic model update

An automatic model update with data from a testbed simplifies the verification procedure.

- Short setup time

A model that is easy to populate reduces expensive setup time.

- Easy to interpret

A model that someone with a background in practical electronics can interpret simplifies the communication at Renault Trucks.

**Support functions**

Support functions are necessary for a product to function properly.

- Transfer of data from test to model.

**Undesired functions**

Functions that add unnecessary complexity.

- Adaptions

The model should be simple, no adaptions for e.g. other machine types than PMSM.

**Verification of functions**

Each required function is verified by using the methods presented in Table 3

*Table 3 Methods to verify required functions.*

| Function | Verification |
|---|---|
| Inputs and outputs | Unit analysis |
| Accuracy | Correlation of model and measurements |
| Stability | Tests in Simulink |
| Performance | Tests in Simulink |
| Modularity | Only MathWorks software |
| Supplier compliance and data | Study agreements |
| Model support and adaption | Interviews |

## 3.2 Specification of requirements

The specification of requirements states the requirements and desires put on the DS2 model by Chalmers University and Renault Trucks. To establish a holistic view, interviews are performed at Renault Trucks. The desires can be weighted from 1-5, where 5 is most essential. The final specifications are presented in Annex I.

## 3.3 Existing drive system models

There are several DS models in use today, both in academia and in industry. To avoid reinventing an existing product and reduce development effort, models in use are identified and briefly presented in this chapter. The identification is carried out through a literature study and interviews with professors at Chalmers University and Renault Trucks employees. Identified model subsystems are analyzed in chapter 0.

### 3.3.1 Renault standard

Renault Trucks has a model of a DS, called Renault standard (Rstd). A system overview is presented in Figure 6. The model is thought to be useful for evaluations in early concept phases.

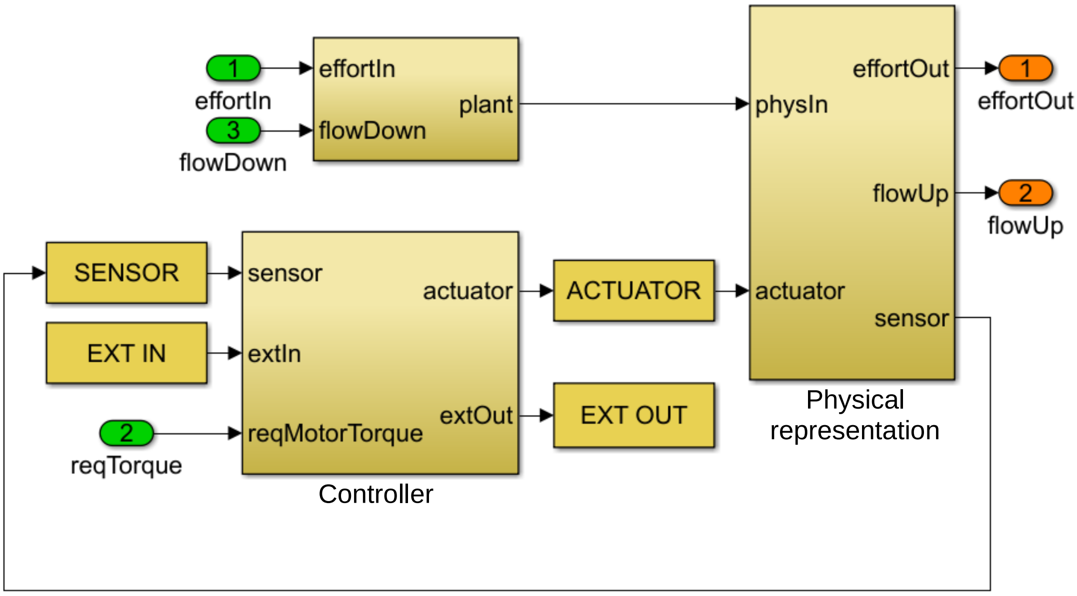


*Figure 6 Overview of Renault standard DS model.*

### 3.3.2 Renault advanced

Renault Trucks has an advanced model of a DS, called Renault Advanced (Radv). The system has the same structure as the Rstd model presented in Figure 6. It enables high model accuracy by using data from Computer Aided Design (CAD) drawings of PMSM.

### 3.3.3 Chalmers general model

A model of a DS developed at Chalmers University is in this report called Chalmers General (CG) drive system model [17]. A system overview is presented in Figure 7. The model is studied in the course ENM076 at Chalmers University as well as in following PhD dissertations:

- Design and assessment of battery electric vehicle powertrain, with respect to performance, energy consumption and electric motor thermal capability, by Emma Arfa Grunditz [18].
- Efficiency analysis of drive train for an electrified vehicle, by Ali Rabiei [19].

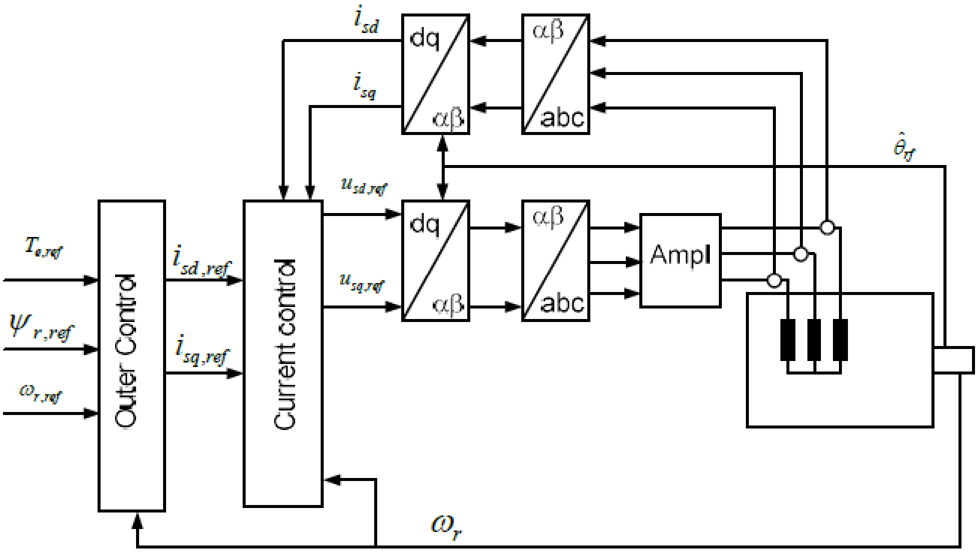
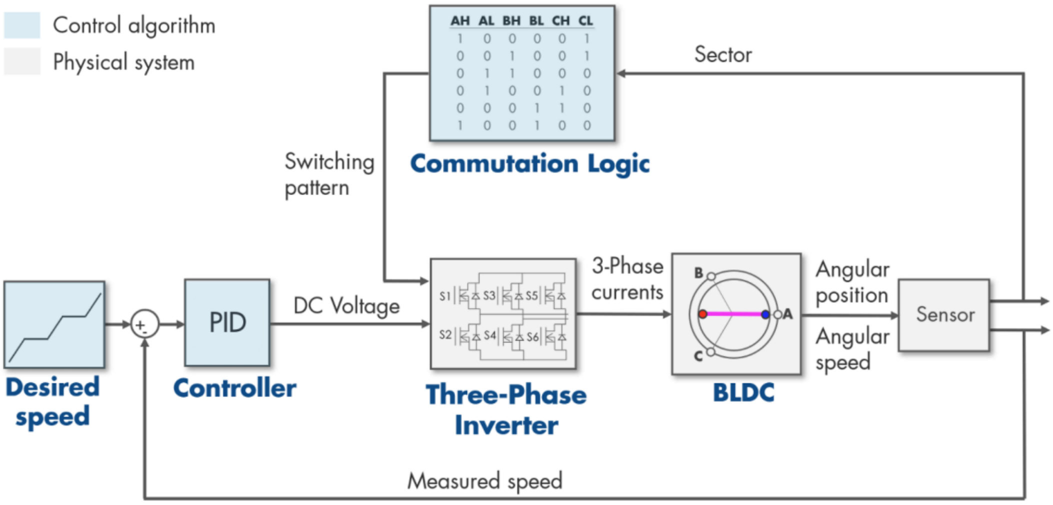


*Figure 7 Overview of CG drive system model [17]. With courtesy of M. D. X. H. Stefan Lundberg.*

### 3.3.4 MathWorks model

A model of a DS with a Brushless DC (BLDC) motor or a PMSM, called Simscape Motor Control (SMC) is developed by MathWorks in their software Simscape electrical. A model overview is presented in Figure 8. Simscape can solve equations based on desired output and therefore makes it simpler to reuse a model [20].



| AH | AL | BH | BL | CH | CL |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 1 | 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 | 0 |
| 1 | 0 | 0 | 1 | 0 | 0 |

*Figure 8 Overview of MathWorks SMC representing a DS with a BLDC motor [20]. With courtesy of (c) 2020, The MathWorks, Inc.*

# 4 DS1 and DS2

In this chapter, the intended use of DS1 and DS2 and their models are presented as well as specifications and control considerations.

## 4.1 Use of hardware

The DS hardware in this project is intended to be used in a 48-volt mild hybrid vehicle with a P3 ExSAM architecture, which is a parallel powertrain architecture. The DS will be used for regenerative braking and torque assist. There are several pros and cons of 48V systems compared with higher voltage systems, such as 600V systems. Systems using 48V have a lower cost and are easier and safer to handle compared to 600V systems but have higher operating currents. A standard for 48V systems is ISO 21780, that describes 48V system requirements in vehicles.

### 4.1.1 Vehicle-level energy analysis

This section presents an example of how much torque and power a DS needs to produce to drive a truck in pure electric mode. Then a DS specification for a pure electric truck on the market is presented and compared with the example. This enables a discussion of DS torque requirements in trucks. A Matlab script that can be used for torque and power estimations called *EstimateMotorSize* follows the outline in this section. It is found online via the bibliography [21].

A truck interacts with the external environment and its traction force $F_{tr}$ that is provided by the powertrain can be described by the fundamental equation:

$$F_{tr} = F_{res} + F_{act} \tag{1}$$

The terms in (1) are composed of the terms:

$$F_{res} = F_{wheel} + F_{aero} + F_{mechanic} + F_{slope} \tag{2}$$
$$F_{act} = M_{tot} \cdot \gamma \tag{3}$$

Eq.(2) states that the resistance $F_{res}$ depends on the wheels $F_{wheel}$, aerodynamic drag $F_{aero}$, mechanic losses in transmission $F_{mechanic}$ and the slope of the road $F_{slope}$. The acting force $F_{act}$ in (3) is the total mass $M_{tot}$ times the vehicle acceleration $\gamma$.

For a standard truck, such as Volvo FL electric, driving at 40 $km/h$ on a flat road, the terms are in percentage of the sum $F_{res}$ estimated to:

$$F_{wheel} = 62\%$$
$$F_{areo} = 29\%$$
$$F_{mechanic} = 9\%$$
$$F_{slope} = 0\%$$

The percentage of (1) terms during the same conditions are estimated to:

$$F_{res} = 50\%$$
$$F_{act} = 50\%$$

The percentages are taken from a report from Renault Trucks. The traction in (1) can be calculated as in

$$F_{tr} = \frac{C_m \cdot r_g \cdot \eta_{tr}}{r_{tire}} \tag{4}$$

where $C_m$ is the torque provided by the DS, $r_g$ is the global transmission ratio, $\eta_{tr}$ is the global transmission efficiency and $r_{tire}$ is the wheel radius.

A pure electric truck should be able to meet all acceleration requirements on the roads. An example when an extreme acceleration is required is an entry onto a highway via an acceleration ramp. An example of an acceleration ramp is the E45 NOAB ramp in Sweden. It is flat and 180 meters long. The ramp entry speed is low and can be assumed to be zero. The required speed to enter the highway from the ramp is 70 km/h. In this simple example a DS can be requested to deliver a constant torque, resulting in a constant acceleration. By using the simple estimation of traction, the required acceleration $\gamma$ cam be calculated using:

$$V_{avg} = \frac{V_{final} - V_{init}}{2} \tag{5}$$

$$s = \gamma \cdot t \cdot t = V_{avg} \cdot t \rightarrow \frac{s}{V_{avg}} = t \tag{6}$$

$$\gamma = \frac{s}{t^2} \tag{7}$$

In the equations above $V_{avg}$ [m/s] is the average speed on the ramp, $s$ [m] is the length of the ramp and $t$ [sec.] is the time on the ramp. For this example truck, the estimation of a DS torque requirement is calculated using the parameter values presented in Table 4, which resemble Volvo FL electric parameters.

*Table 4 Parameters used to make the torque estimation.*

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $r_g$ | Vxl [ratio] | $F_{res}$ | $F_{act}$ [Nm] | $V_{final}$ | 70 [km/h] |
| $M_{tot}$ | 16 000 [kg] | Tires | *445/75R16* | $V_{init}$ | 0 [km/h] |
| $\eta_{tr}$ | 1 [%] | $r_{tire}$ | 0,53 [m] | s | 180 [m] |

The example truck is required to accelerate with 0,52 $m/s^2$ to be able to access the highway at desired speed. Characteristics calculated using the script *EstimateMotorSize* are presented in Table 5.

*Table 5 The example truck's estimated characteristics.*

| **Example truck** | |
|---|---|
| Total weight | 16000 [kg] |
| Electric motor torque | 425 [Nm] at Vxl = 21,2 |
| Motor power (max) | 333 [kW] |

The rotation per minute (rpm) of the tires at $V_{final}$ is 345 rpm. A selection of a global gear ratio $r_g = 21{,}2$ in the standard truck results in a DS torque requirement which corresponds to Volvo FL DS torque. The DS operating point is then 7323 rpm at a vehicle speed of 70 km/h. Volvo FL electric, that is available on the market, has the characteristics presented in Table 6.

*Table 6 Volvo FL Electric characteristics.*

| **Volvo FL electric** [22] | |
|---|---|
| Total weight | 16000 [kg] |
| Electric motor torque | 425 [Nm] |
| Motor power (max/ continuous) | 200/165 [kW] |

The example results in a higher power requirement compared to Volvo FL electric's rated power. An improved model including aerodynamic drag and losses can make the estimation more accurate. By using acceleration requirements in this project, a torque span is determined to 0 < DS nominal torque < 9.0/$r_g$ [kNm], ranging from torque assist to pure electric drive.

## 4.2 Use of models

In this section, the intended use of the DS1 and DS2 models are presented. The models of DS1 and DS2 are included in a database called the Global Simulation Platform (GSP) that partially contain Matlab and Simulink models. The models in the GSP are used to simulate the motion of a vehicle and calculate gradeability, recovered energy from regenerative braking and fuel consumption. A simulation overview of a truck concept where a DS is part of a vehicle is presented in Figure 9.

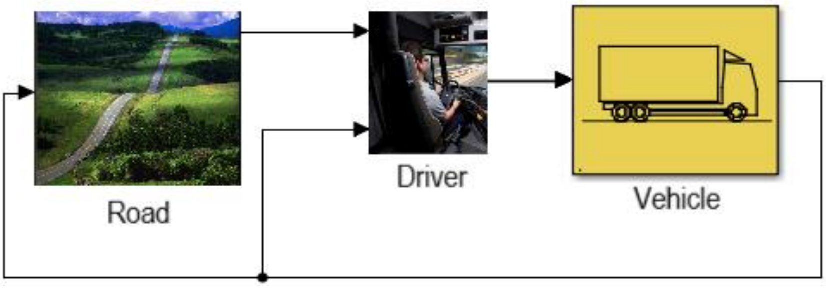


*Figure 9 Simulation overview of a truck concept in the GSP [13]. With courtesy of Volvo Group AB.*

The simulation concept in Figure 9 consists of the following three components:

- *Road/environment:* represents a road topography and an environment that affect the vehicle based on a position. Several drive cycles are available in the GSP. The results from a cycle simulation can be compared with measured data from a truck that drives the real cycle.

- *Driver:* represents a driver's acceleration and brake pedal positions according to the road conditions. It regulates the speed towards a set point. Several signals to the powertrain are set in the component, such as selection of gear.

- *Vehicle:* represents a powertrain concept where parts such as an ICE, a DS, a gearbox, wheels and auxiliaries are included [23].

The parts and interface of the vehicle are of interest since the DS models are a part of the vehicle. An overview of a vehicle model with the P3 ExSAM powertrain architecture is presented in Figure 10. The required DS interface is stated in the specification of requirements.

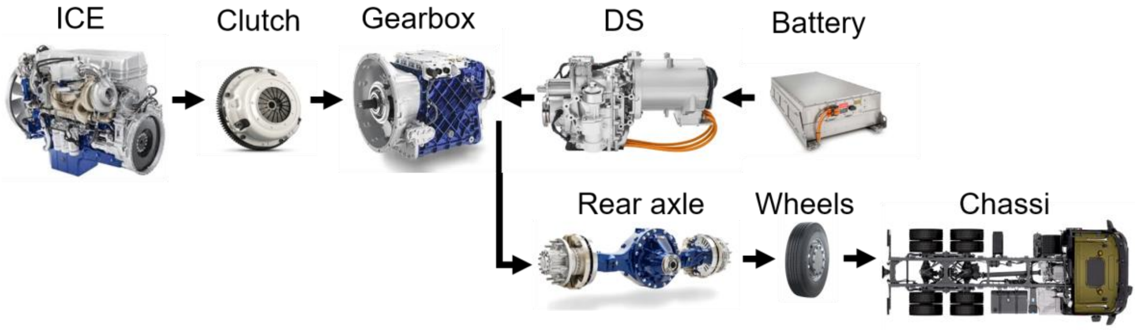


*Figure 10 Overview of main parts of a vehicle model with the powertrain architecture ExSAM P3 in GSP. With courtesy of Volvo Group AB.*

## 4.3 Specifications

In this chapter, the DS1 and DS2 are described. The description of DS2 is used in the development of its model. The term “machine” is used for a unit that can be used both as a generator and a motor.

Following conventions are used:

- Counterclockwise rotation when facing the front side with the shaft of the DS results in a positive speed.
- A positive torque means that it acts in the direction of positive speed.
- A positive current means that the current is supplied from a battery.

### 4.3.1 DS1

DS1 consists of a PMSM, an electronic control unit and an inverter. It uses a Field Oriented Control (FOC) algorithm. The DS1 specifications are stated in Table 7.

*Table 7 Specification of the DS1 hardware.*

| **Specification** | | | |
|---|---|---|---|
| Nominal supply voltage | 48V DC | Sensor rotor | Encoder |
| Operating voltage | 36 < U < 56 | Communication | CAN |
| Control | Torque control | Cooling | Water |

An error is calculated to control the DS based on the Process Variable (PV) and a Set-Point (SP). The machine can change from torque control to speed control to protect the machine by applying a torque in the opposite direction of the rotation. If the machine cannot provide enough torque to reduce the speed an active short circuit is activated to protect the system. The active short circuit protects the inverter transistors from overvoltage caused by induced voltage in the machine. A model of DS1 exists and it is not modified as stated in section 1.3.

### 4.3.2 DS2

DS2 consists of a PMSM, an electronic control unit and an inverter. It uses a FOC algorithm. The DS2 specifications are stated in Table 8.

*Table 8 Specification of the DS2 hardware.*

| **Specification** | |
|---|---|
| Nominal supply voltage | 48V DC |
| Operating voltage | 36 < U < 52 |
| Machine | A permanent magnet synchronous machine 48V with 6 poles. |
| Inverter | Uses a bridge with power MOSFETs for switching. It can short-circuit back EMF that the PMSM generates to prevent undesired currents. A torque derating is applied at high internal temperatures to protect the system from overheating. |
| Control | Torque control |
| Communication | CAN |
| Cooling | Water, 5 liter/min |
| Selected sensor signals | Rotor position based on encoder signal<br>Supply voltage<br>Supply current<br>Estimated torque<br>Phase currents<br>Stator temperature |

### 4.3.3 Per-unit system

In this thesis, some specifications are expressed in a per-unit system. The per-unit system (pu.) is the expression of system quantities as fractions of a defined base unit quantity. A normalization of quantities to a common base simplifies calculations and makes it easier to find erroneous values. A base value $z$ is defined as in (8) where $Id$ and $Iq$ are the currents at the DS rated torque. A current vector $v = a + j \cdot b$ can be transformed from its cartesian form into polar form by using (9), where $|v|$ is the magnitude and $\arg v$ is the angle between $a$ and $b$. The arctan function is defined for (-$\pi, \pi$], if $a \leq 0$ a compensation is performed. The current vector $v$ can be expressed in pu. of the base unit $|z|$ as a vector $v_{pu}$ by using:

$$z = Id + j \cdot Iq \tag{8}$$

$$\arg v = \begin{cases} arctan(b/a) & \text{if } a > 0 \\ arctan(b/a) + \pi & \text{if } a < 0 \end{cases} \qquad |v| = |a^2 + b^2| \tag{9}$$

$$v_{pu} = \frac{|v| \cdot (\cos(v) + j \cdot \sin(v))}{|z|} \tag{10}$$

## 4.4 Control theory

In this section the FOC is briefly reviewed. Both DS1 and DS2 use FOC. First, a voltage control of a DC motor is presented to introduce the topic of FOC.

### 4.4.1 Voltage control of a DC motor

A direct current (DC) motor can have permanent magnets in the stator and coils in the rotor. The rotor is then connected to a voltage source by brushes. The rotor and the connection surface are divided into segments which makes it ideally possible to get a constant angle between the magnetic fields in the rotor and the stator. For optimal performance the rotor circuit should have a current magnetomotive force that is 90 degrees in relation to the magnetic flux of the stator. The magnetic field relations produce a torque that turns the rotor. The torque depends on the current that gives rise to the magnetic field in the rotor. The current is controlled by changing the voltage, often by using Pulse Width Modulation (PWM). The PWM turns on and off the voltage source, using transistors, which makes it possible to control the average voltage and therefore the current. PWM gives rise to a voltage ripple that is damped by the inductance in the machine, but a PWM has several impacts on the motor performance due to harmonic components in voltage and current [24]. A DS with a DC motor is presented in Figure 11. A controller is used in the DS to control the torque. An error is calculated between a desired torque expressed as a current and the measured current. The error is used in a PI controller to put a demand of the pulse length in the PWM module. It regulates the voltage, which determines the current and indirect the torque.

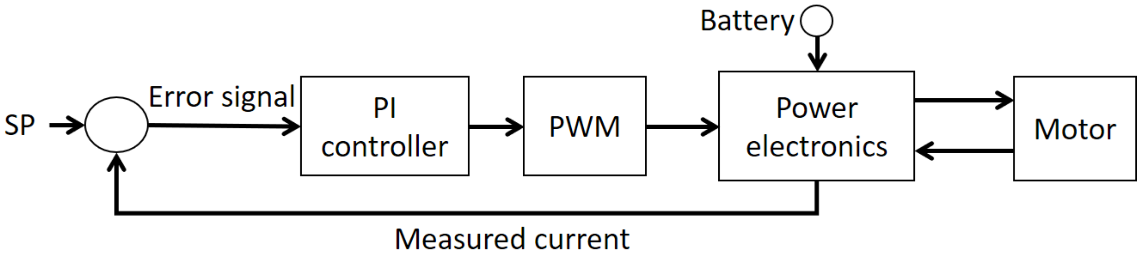


*Figure 11 Example of a DS with a DC motor. Its torque is regulated using feedback from the current measurement.*

### 4.4.2 Field oriented control

Field Oriented Control (FOC) of electric machines was first introduced by F. Blaschke at Siemens in the late '60s. The control method creates a magnetic vector in the stator with a relative angle to the rotor magnetic field by controlling the currents in the stator. The currents are measured and controlled by using the error between the current Set-Point (SP) and the measure. This is achieved by changing the average voltage over the stator, by using PWM. The current SP is controlled by using the error between a target speed SP and the motor speed, which is based on angle measurements. The angle is also used in Park transformations, which simplify current control calculations, together with Clark transformations. DS1 and DS2 have encoders to measure the angle. To achieve the desired magnetic vector, calculations on a processor are required. This made the systems more expensive at their introduction in the '70s than today. An overview of FOC for an electric machine M is presented in Figure 12. An introduction video of FOC for electric machines is *Field Oriented Control of Permanent Magnet Motors* by Dave Wilson, where the overview is explained [25]. DS with permanent magnets in the rotor using FOC do not have any electric connection with the stator, which reduces the need of maintenance. The control method gives a high torque, a smooth operation and high efficiency over a wide speed range. The encoder can in some cases be replaced by measurements of the signals that the machine provides, called sensorless control.

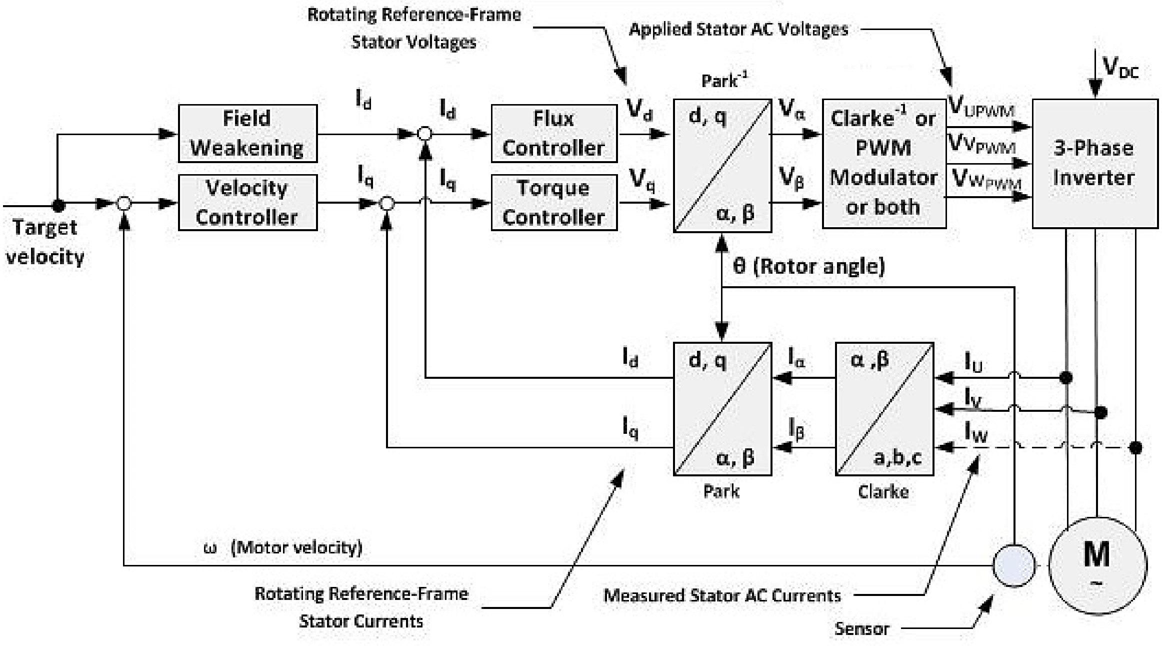


*Figure 12 Overview of FOC for an electric machine [26]. With courtesy of Cblambert.*

### 4.4.3 MTPA control

For DS vehicle applications it is desirable to achieve fast acceleration, which can be achieved by the Maximum Torque Per Ampere (MTPA) control method. The idea of MTPA control is to minimize the stator currents magnitude for an achieved torque. The control makes it possible to use power converters with lower power ratings compared to other control approaches and can reduce hardware cost [27]. The control method also results in high power efficiency.

### 4.4.4 Derating

Derating is the choice of operation of a DS at less than its rated maximum abilities in order to prolong its life and improve its reliability [28]. A torque derating is used to reduce the DS temperature, which is a factor that affects the system's reliability and lifetime. Neodymium permanent magnets get a weaker magnetic field at 80°C and can get permanent damages at 200°C. An inverter has a low thermal capacity due to the low mass of the transistors and they can overheat and melt after a short period of peak power operation. Short circuits can occur in the stator if the insulation is damaged by heat. An example of an insulation is NEMA class H. It is specified for a max temperature of 180°C and 165°C at thermal equilibrium, which occurs under continuous load, with an ambient temperature of 40°C. A margin for hotspots in the windings exists. The insulation deteriorates at an increasing rate at higher temperature, which approximately doubles for every temperature increment of 10°C. The insulation loses mechanical strength during rated operation. For example, class F insulation loses half of its mechanical strength after operating for about 2,2 years at its rated temperature [29] [24].

A controller can use temperature-based events to derate a DS torque and power in order to prolong its life and improve its reliability. Derating times can in general be calculated as the time between the events presented in Figure 13 and Table 9. When using a truck, the intervals stated in Table 10 are of interest. In this project, a DS derated power output is assumed to be equal to the DS nominal power. A natural power reduction also occurs at high temperature due to increased winding resistance. Figure 14 illustrates the effect of torque derating.

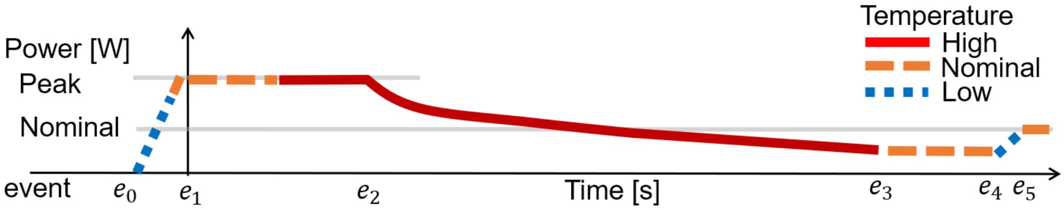


*Figure 13 A general overview of power derating.*

*Table 9 Derating events.*

| | | | |
|---|---|---|---|
| e0 | Test start, load DS | e3 | Derated output |
| e1 | Peak power | e4 | Derating off |
| e2 | Derating on | e5 | Nominal power |

*Table 10 Intervals of interest.*

| | | | |
|---|---|---|---|
| e1-2 | Max boost time | e2-5 | Derating time from peak to nominal power |

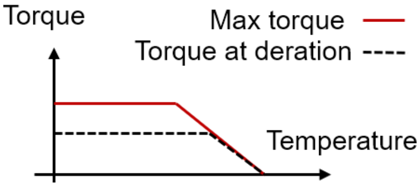


*Figure 14 Torque derating.*

# 5 DS2 model

In this chapter, DS2 subsystems are proposed, existing models are analyzed and the DS2 model is presented. The subsystems are a controller, an inverter and a PMSM. A selection of subsystems used to implement the DS2 model is performed in chapter 5.3.

## 5.1 Concept generation

In this section, model concepts proposed by parties in the project are presented. They are presented to capture existing and innovative ideas.

### Modelling of PMSM

Two methods to create a PMSM model are proposed. A model based on lookup tables, that can be populated using system identification tools. A machine model that uses differential equations, derived from the machine's geometry and material properties. This makes it possible to create an accurate model without own tests because the material parameters have already been tested, often with high accuracy.

### Modelling of controller

Two methods are proposed. A control that uses Proportional, Integral and Derivative (PID) control. An emulation of the controller, to take into account more system characteristics.

### Modelling of inverter

An inverter has fast switching components, whose behavior takes a lot of effort to calculate. A model that represents current constraints can instead be used to reduce computational effort. Another option is to use a representation of average currents and losses during clock cycles.

## 5.2 Analysis of existing DS models

In this section, the DS models in section 3.3 are analyzed to find and select subsystems that are suitable for implementing the DS2 model. Due to the scope of the project, the concepts in section 5.1 and MathWorks SMC model are not studied further.

All models in section 3.3 can be divided into a controller, an inverter and a PMSM. An additional subsystem called Priority TMS/EMS is required to use the DS in the GSP. The subsystem is omitted in this report since it is independent.

Subsystem options to model DS2 are selected after a process. The subsystems are analysed and processed through an elimination and then a selection process. The best subsystem option, given the information in possession, is then selected. The selected subsystems are presented in Table 11.

*Table 11 The best model options, given the information in possession.*

| | |
|---|---|
| Motor | Rstd |
| Inverter | Rstd |
| Controller | Rstd |

### 5.2.1 Electric machine

In this section, the machine models in section 3.3 are analyzed.

**Renault standard**

The machine model is divided into calculations of current, losses and thermal energy, the division is presented in Figure 15. The system where losses are calculated contains both the losses in the inverter and the machine, but they are separated in the subsystem.

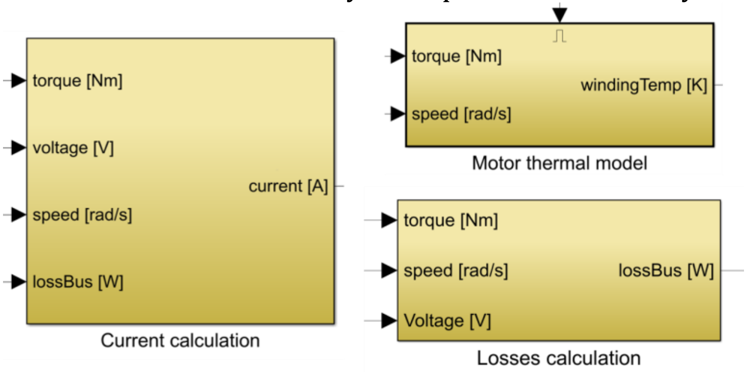


*Figure 15 Rstd machine subsystems.*

Data from tests are interpolated in the subsystems to get functions. Interpolation methods using e.g. Lagrange polynomials, takes measurements points and approximates a continuous function that is valid for the points and intermediate values [30]. Simulink has several interpolation blocks e.g. 2-D Lookup Table, called a map. The function block interface is presented in Figure 16. These blocks and simple calculations represent the machine characteristics.

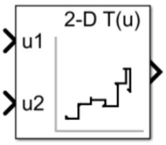


*Figure 16 Simulink 2-D Lookup table.*

**Renault advanced**

The Radv machine model has the same structure as the Rstd model. Its machine is populated using an data derived from a drawing created in a CAD program. Several CAD programs, such as CATIA V5, can generate a finite element model. The program use material properties, originating from test results, and geometry to create the model [31]. This model is then exploited to create a state-space representation of the machine, using simplifications. The simplifications give higher performance but lower accuracy in simulation.

State-space models are models that use state variables to describe a system by a set of first-order differential or difference equations, rather than by one or more nth-order differential or difference equations [32]. The state-space model structure is efficient when using computational software. In the Radv, state-space functions blocks are used to represent the machine, such a block is in Figure 17.

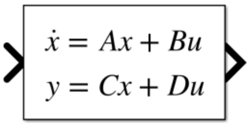


*Figure 17 Continuous state-space representation in Simulink.*

No actual measurements on the machine are required to populate the model, it reduces modelling lead times. The method to populate the model can give an accurate model but requires access to e.g. machine drawings. An accurate drawing enables an accurate model.

**Chalmers general model**

The CG model is an analytic model that uses machine parameters to represent the system. The parameters used to represent the system are stated in Table 12. A description of the system equations is given in the course material for ENM076 at Chalmers, as well in the two PhD dissertations referred to in section 3.3.4.

*Table 12 PMSM parameters used to populate the CG model.*

| | | |
|---|---|---|
| $R_S\ [\Omega]$ | $J_{PMSM}\ [kgm^2]$ | $\Psi_m\ [Wb]$ |
| $L_{aa0}\ [H]$ | $L_{ab0}\ [H]$ | $L_{aa2}\ [H]$ |
| $n_{s,rated}$ [rpm] | $f_{s,rated}$ [Hz] | $P_{rated}$ [W] |
| $V_{s,rated}$ [V] | $I_{s,rated}$ [A] | |

### 5.2.2 Inverter

In this section, the inverter models in section 3.3 are analyzed.

**Renault standard**

The inverter is divided into three subsystems presented in Figure 18 and Figure 19, they are:

- Two subsystems that set torque and power limits with respect to machine specifications. The subsystems are populated using table data, in maps.
- An inverter thermal model that calculates the energy balance in the inverter over time, as a function of speed, voltage and machine torque. The supplied heat energy to the system is removed via the cooling system.

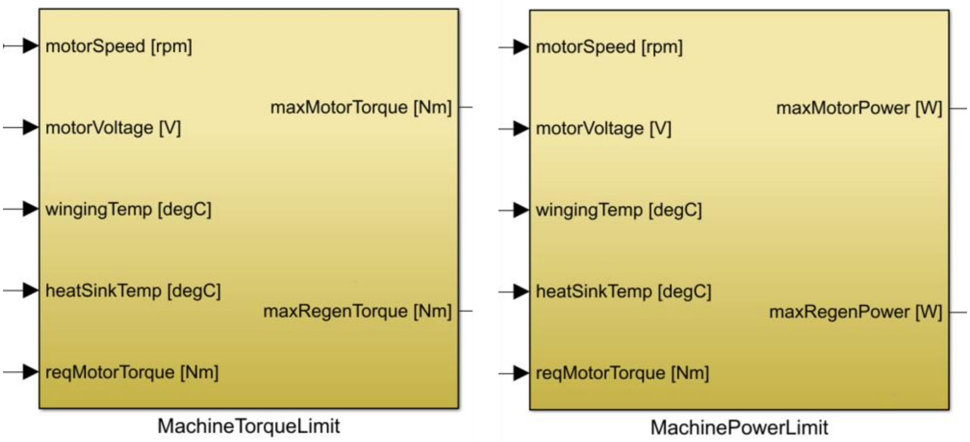


*Figure 18 Rstd power and torque limitations.*

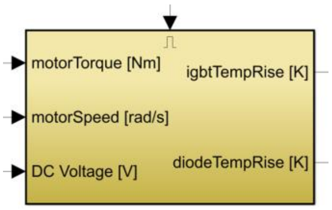


*Figure 19 Rstd inverter thermal model.*

**Renault advanced**

The inverter in Radv has the same structure as Rstd but uses root mean square current, modulation factor, speed and inverter temperature inputs to calculate the heat supplied to the inverter. The inverter is divided into following subsystems:

- Torque and power limitation subsystems, as presented in Figure 18.
- A more advanced Electric Motor Drive (EMD) thermal model, which uses state space representations and more inputs for e.g. the base plate temperature, as presented in Figure 20.

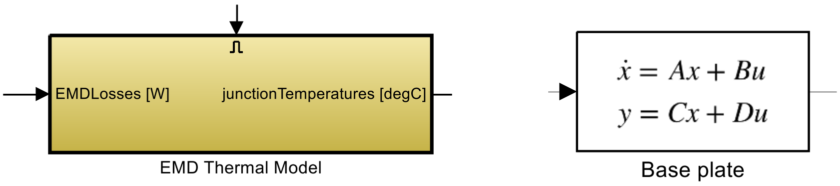


Figure 20 A part of Radv subsystem for an inverter called EMD that includes a model of a base plate.

#### Chalmers general model

The CG model is an analytical model that represents the inverter with a block called a converter, as presented in Figure 21. A voltage limit value is set in the converter.

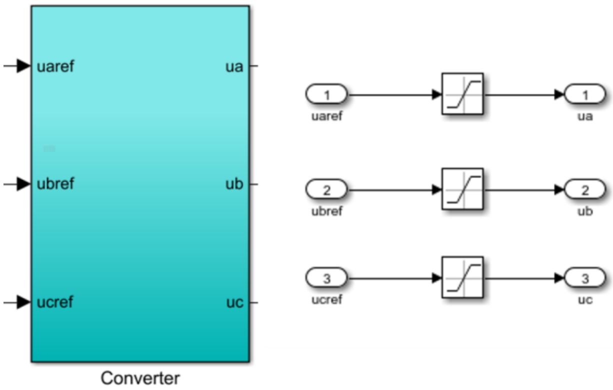


Figure 21 The CGM converter uses voltage limits. With courtesy of M. D. X. H. Stefan Lundberg.

### 5.2.3 Controller

In this section are the controller models in section 3.3 analyzed.

#### Renault standard

The Rstd controller, if set in control mode 1, uses an error between the set point speed and the process speed to set a request of machine torque by a PID gain of the error. An overview of the Rstd controller is presented in Figure 22.

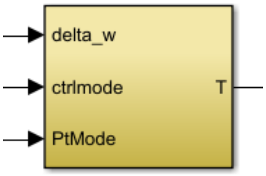


Figure 22 Rstd controller, a PID regulator with different control modes.

#### Renault advanced

The Radv model use the same controller subsystem as the Rstd model.

#### Chalmers general model

The CG model controller uses Id and Iq currents to control the machine as described in section 4.4.2. Park and Clark transformations are used to simplify these calculations. An overview is given in Figure 23.

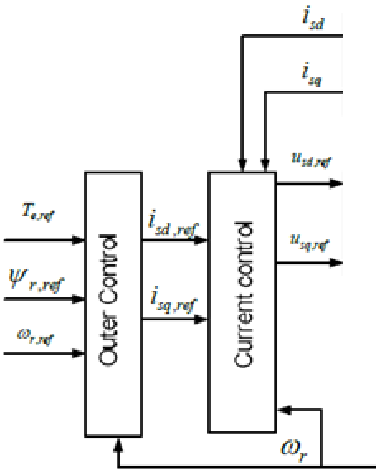


Figure 23 Functional overview of the CG model controller [17].

## 5.3 Subsystem selection

In this section, the models analyzed in section 5.2, go through an elimination process and then the best model option selected. Each subsystem either fulfills a requirement (x) or not (-) in the elimination process. A model has an advantage (+) or a disadvantage (-) compared to another model in the selection. The specification of requirements is found in annex I. The selection process is based on desires put on the subsystem; they are included in annex I.

### Electric machine

In this section, a machine model is selected to implement the model of DS2 after an elimination process presented in Table 13.

Table 13 Elimination matrix machine.

| Criteria<br>Model | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Renault standard | x | x | x | x | x | x |
| Renault advanced | x | x | - | x | x | x |
| Chalmers general model | x | x | x | x | x | x |

The Radv model do not fulfill the requirement C5 *Provider compliance and data* as no CAD drawings of the DS2 are available. Radv machine model is therefore eliminated and therefore not further evaluated. A comparison of the remaining models is presented in Table 14.

Table 14 Comparison of machine models.

| Model<br>Criteria | Renault standard | Chalmers general model |
|---|---|---|
| J1 | R | - |
| J2 | E | - |
| J3 | F | + |

The CG model of the machine is harder to setup and integrate in GSP than Rstd. The maps in the Rstd model is suitable when using data from a testbed. The CG model is analytical and can be easier to explain and thus interpret. The Rstd machine model is selected to implement the model of the DS2 machine.

### Inverter

In this section, an inverter model is selected to implement the model of DS2 after an elimination process presented in Table 15.

*Table 15 Elimination matrix inverter.*

| Criteria / Model | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Renault standard | x | x | x | x | x | x |
| Renault advanced | x | x | - | x | x | x |
| Chalmers general model | x | x | - | x | x | x |

The CM model and Radv model do not fulfill the requirement C5 *Provider compliance and data*, as not all data required is available. Therefore, the Rstd inverter model is selected to implement model of the DS2 inverter.

**Controller**

In this section, a controller model is selected to implement the model of DS2 after an elimination process presented in Table 16. The Rstd and Radv models use the same control subsystem, therefore only the Renault standard controller is evaluated.

*Table 16 Elimination matrix controller.*

| Criteria / Model | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Renault standard | x | x | x | x | x | X |
| Chalmers general model | x | - | x | x | - | - |

The controller used in the CG model is adapted for a more advanced machine than the selected one. It is not possible without adaptions to use the CG control model with selected subsystems. The Rstd model controller is therefore selected to implement the model of the DS2 controller.

## 5.4 DS2 implementation

The machine, inverter and controller of Renault standard model are selected to model DS2. An overview of the system is presented in Figure 6. Both the CG and Radv model remains of interest but in this project, there is not enough data available to implement the models as intended. Data to populate the Rstd model is provided by Renault Trucks due to the lockdown in France during the spring of 2020.

# 6 Verification

A verification (*from Latin 'versus' Truth and fa'cio' to do)* is to prove by good evidence [33]. Verifications of models are essential to be able to assess results from a model simulation. In this verification part of the thesis, measurements from tests of DS hardware and of DS models in simulation are compared to determine a set of deviations. In the tests of DS models, hardware tests are imitated in a virtual testbed. An overview of the verification procedure is presented in Figure 24. The deviations are used to check if the models meet accuracy requirements that are important when assessing simulation results.

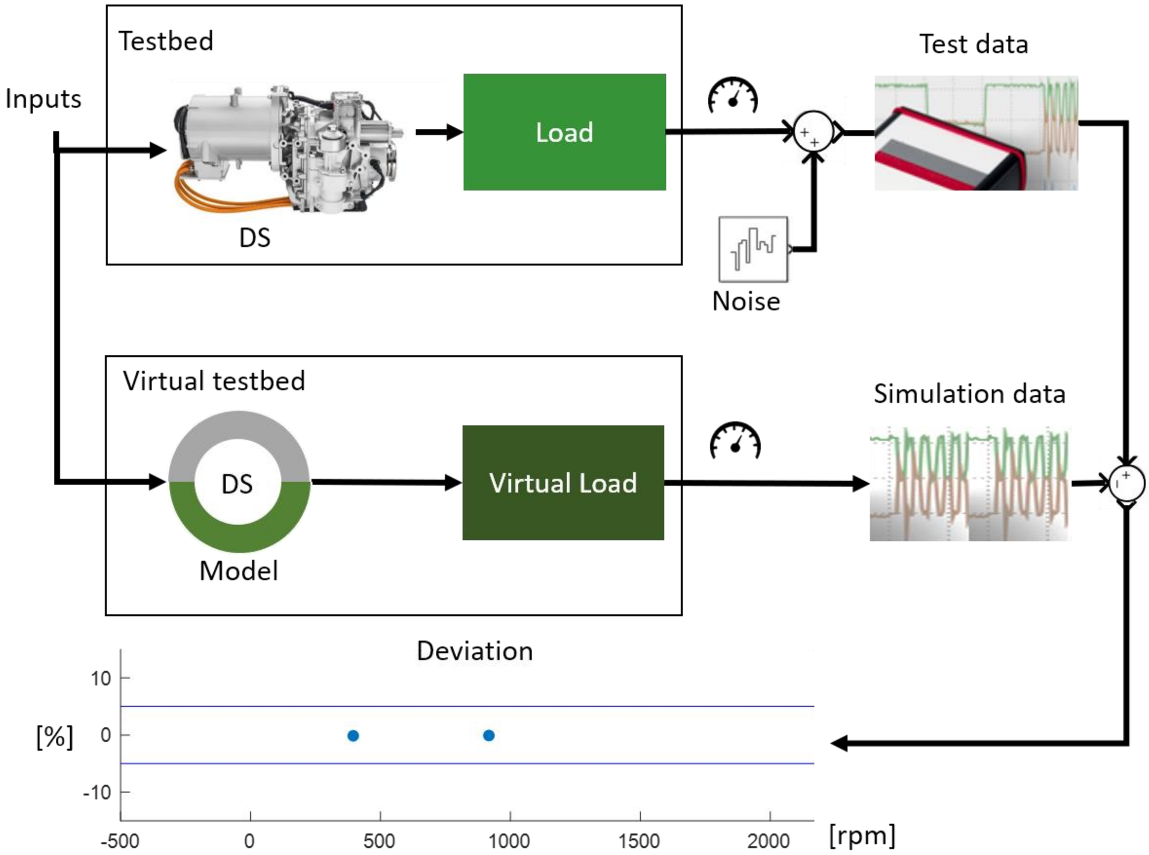


*Figure 24 Verification process. "Electric powertrain" with courtesy of Volvo Group AB.*

A documentation of the verification process is created using Matlab help files to make it possible to trace problems. Verification methods presented in this part of the thesis can be used in mass production, as proposed in chapter 13. A verification where a supplier is unaware of the test procedures can make sure that model discrepancies can be clarified [34].

## 6.1 Simulation assessment

This section introduces how to assess results from a model simulation. A question that arise after a simulation in the GSP is how big fuel reduction is required to return a DS investment. It depends on several terms, such as cost of installing a DS in a powertrain and the reduced fuel consumption. It is not certain that a simulation of a driving cycle that results in a fuel reduction of 2% per kilometer, after including a DS model in the simulation, will actually reduce the fuel consumption. If the model has an uncertainty of e.g. 10%, it is possible that there is no actual reduction in fuel consumption. A verification that results in a negative deviation means that the model has better performance than the hardware, thus the fuel consumption in the simulation is lower than the actual consumption. If the verification results in a positive deviation, the hardware performance is higher than in the model. Therefore, a simulation using such a model does not clarify the actual fuel reduction, which means that an investment opportunity can be lost.

There are several factors that affect a model's uncertainty, such as:

- Model deviations from measurements caused by e.g. model simplifications.
- Uncertainties in the measurement chain.

In this project, a model is accepted if the maximum and minimum value in the set of deviations has a difference that is less than or equal to 10% of the measured values. This accuracy requirement is derived from a hybrid powertrain example called Volvo concept truck [35]. A reference of ± 5% is used in this thesis to simplify the interpretation of the results. All deviations are specified, which makes it possible to assess if the model is accurate enough for some desired simulation, even if it's not accepted in this project.

## 6.2 Sensitivity

A sensitivity analysis is the study of how the uncertainty in the output of a model can be divided and allocated to different sources of uncertainty in its inputs [36]. It helps to prove that a model is valid by not arbitrarily restricting the input space. A sensitivity analysis is performed on DS1 torque for the following input parameters of interest:

- Cooling water inlet temperature.
- Battery voltage.

These parameters are expected to deviate from their nominal values, 65°C and 48V, due to the ambient temperature and battery characteristics, respectively.

### Review of sensitivity analysis methods

Morris method for global sensitivity is a so called one-step at a time method, which means that in each run only one input parameter is given a new value. This method is used since the uncertainties in the inputs can be estimated. Another method to determine the sensitivity of a system is to perform Monte Carlo experiments that are a broad class of computational algorithms that rely on repeated random sampling. Monte Carlo experiments are most useful when it is difficult to use other methods [37].

# 7 Criteria verification

This chapter presents requirements for simulation and verification procedures.

## 7.1 Functions

This section states the functions used in the simulations and verifications.

### Required functions

This section presents the required functions.

- Simulate a DS model in a virtual testbed that imitates a hardware test.
- Plot deviation between measured parameters from hardware and simulation tests.

The set of parameters in Table 17 are required to be verified or simulated in steady state.

*Table 17 Verifications and simulations required.*

| Parameter | Preform | Range | Resolution |
|---|---|---|---|
| Max torque | Verification | As in hardware tests | |
| Max power | | | |
| Efficiency (at max power) | | | |
| Power losses at zero torque demand | Simulation | Motor mode | |
| Derating time from peak to nominal power | | | |

### Desired functions

Functions in this section add value but do not affect the required functions.

- Simulation of max angular acceleration.
- Sensitivity to cooling water temperature.
- Sensitivity to supply voltage.
- Evaluation of measurement uncertainties.
- Simulation of max time in boost mode before derating.

### Support functions

Support functions are necessary for a product to function properly.

- Read and sort BLF files containing CAN data.
- Interpret measurements stored in Matlab files.

### Undesired functions

Functions that add complexity e.g. settings to adapt the models.

### Verification of functions

Each required function in this chapter is verified by using known datasets as input and expected output.

## 7.2 Specification of requirements

A final specification of requirements for the verification procedure is presented in Annex I.

# 8 Tests of DS

In this chapter, the DS test equipment is analyzed. Tests solve a key issue in simulation, that is acquisition of valid data, since it can be obtained from the tests. A testbed that is used in this project is presented in chapter 9.

## 8.1 Existing equipment

In this section, existing test equipment, used to test DS at Renault Trucks, is identified and briefly presented. Renault Trucks uses three levels of system integration when testing DS, from low to high. A DS is first tested in a testbed with low integration that has few external parameters, as presented in Figure 25. This setup is suitable to collect data for a DS model correlation. Then a medium integration test is performed, where environmental conditions are controlled, as presented in Figure 27. The test is suitable when studying powertrain configurations. An integrated test, as presented in Figure 26, is then performed where focus is directed to real operating conditions. Teams at Renault Trucks or suppliers can provide data collected using other test methods, represented by Figure 28. The provided data and the data in the model should not be used for a verification if they come from the same test.

*Figure 25 Renault testbed. "Electric powertrain" with courtesy of Volvo Group AB.*

*Figure 26 In-use vehicle [38]. With courtesy of Volvo Group AB.*

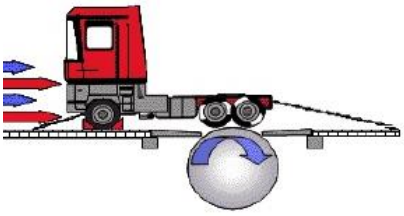


*Figure 27 Vehicle chassis dynamometer [13]. With courtesy of Volvo Group AB.*

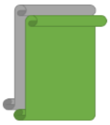


*Figure 28 Provided data.*

## 8.2 Measurements

The objective of a measurement is to determine the value of the measurand. A measurement is only an approximation or estimate of the value of the measurand, thus a statement of the uncertainty of that estimate is required [39]. Data acquisition systems have a measurement chain. By studying it, factors that introduce errors in the measurements can be determined. A general measurement chain that can be used to study errors is presented in Figure 29.

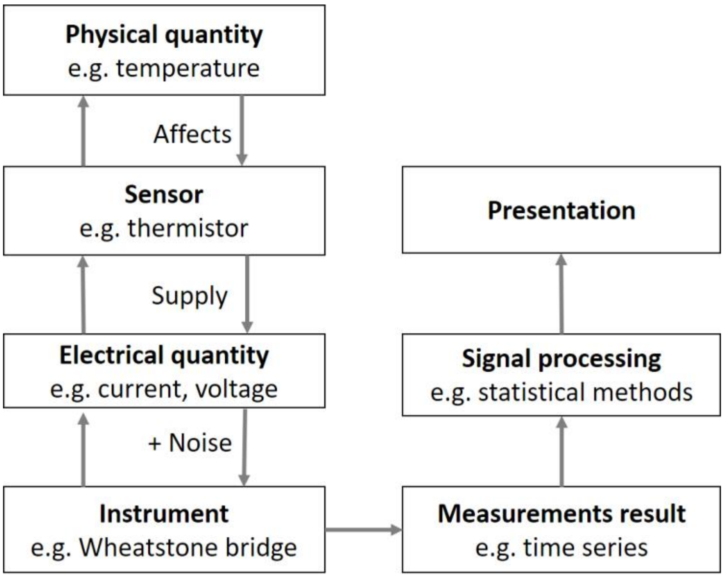


*Figure 29 Measurement chain.*

The errors can be divided into error type A and B.

- A: Random errors, due to the precision of the equipment; precision error.
- B: Systematic errors, also called biased, are due to the use of equipment or the calibration; accuracy error.

In Figure 30 , the error types A precision and B accuracy are illustrated, where the center of the target is the true value.

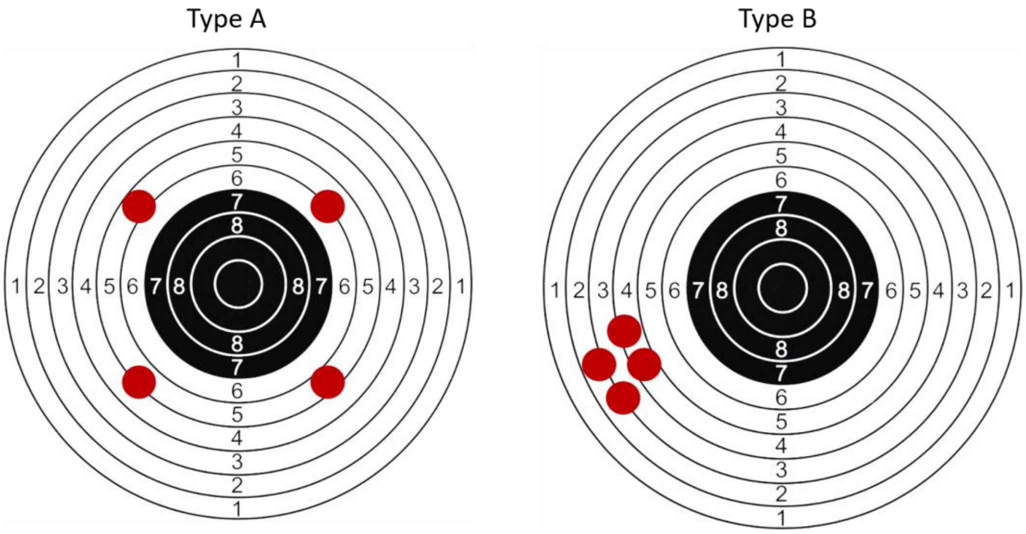


*Figure 30 Measurement error from the true value in the center of type A and type B, measured values are represented by circles.*

Type A errors are often processed by using statistical methods, type B errors can be processed using other methods.

A model has lower accuracy than the measurements, which should be considered when verifying a model using measurements from tests.

Uncertainty means doubt about the validity of the result of a measurement in general. It is a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand. There are several standards such as *Guide to the expression of uncertainty in measurement* (GUM) that are useful for more exhaustive studies of measurement errors [40].

Another important aspect when making measurements is the locations of the sensors. A temperature sensor placed too far away from e.g. a heat source will not give the true temperature in the heat source.

## 8.3 Selection of test equipment

In this section, the test equipment presented in section 8.1 is ranked from the most to least suitable for testing DS1 and DS2. The ranking is based on the number of test parameters and the information available about the test equipment.

List of test methods from the most to least suitable:
1. Testbed
2. Suppliers data (testbed)
3. Vehicle chassis dynamometer
4. In-use vehicle

In this project, a testbed at Renault Trucks is selected to test DS1, presented in chapter 9. The supplier data is collected from a testbed setup for both DS1 and DS2.

# 9 Testbed

In this chapter, the Renault testbed selected in chapter 8, and procedures for testing DS on it are described so measurement uncertainties can be traced and tests repeated. DS1 is tested with the Renault testbed.

## 9.1 Testbed setup

The testbed setup is presented in Figure 31, where a DS is connected to an electric dynamometer via a shaft. Both are controlled via a computer. The DS is assumed to have an ideal supply voltage and can use a load resistor if it generates power to dissipate it. The dynamometer has an AC/AC converter connected to the grid that can both supply power and act as a load.

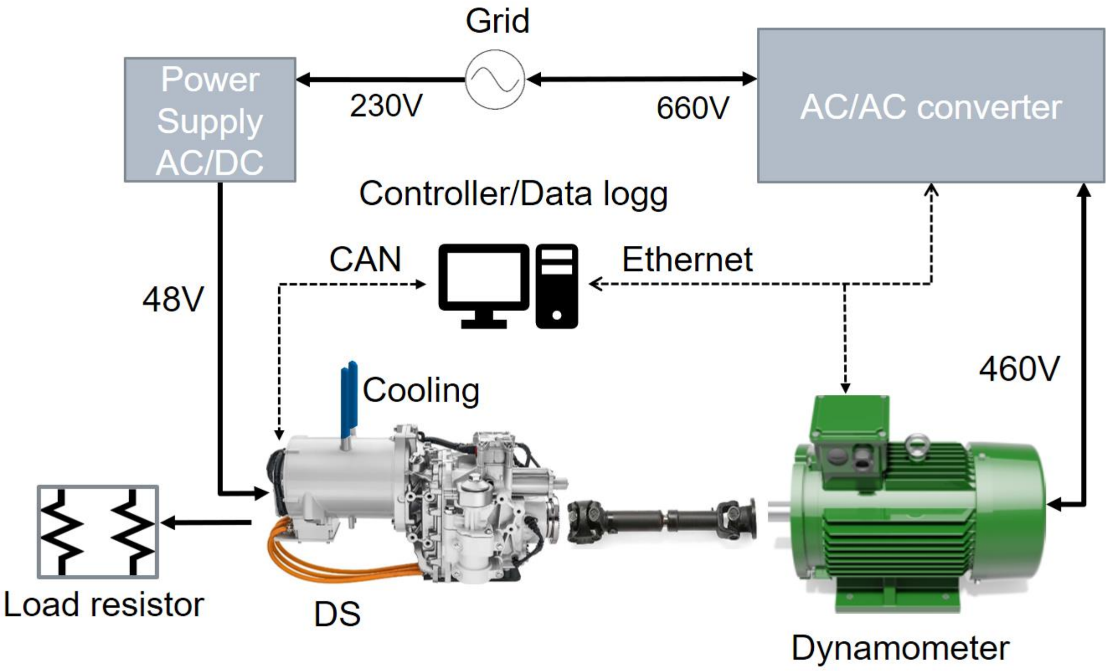


*Figure 31 Renault testbed setup. "Electric powertrain" with courtesy of Volvo Group AB.*

### 9.1.1 Measurements, sensors and instruments

This section presents the measurements, instruments and sensors used. The physical quantities in Table 18 need to be measured at the testbed in order to fulfil the specification of requirements.

*Table 18 Measurements required to be performed at the Renault testbed.*

| **DS** | |
|---|---|
| Speed [rpm]<br>U supply [V]<br>I supply [A] | Torque shaft [Nm]<br>Temperature machine winding [°C] |
| **Dynamometer** | |
| Speed [rpm] | |

At the Renault testbed during tests of DS1, signals are logged via DS1 Controller Area Network (CAN). It is not recommended to use DS1 internal measurements to collect data when high accuracy is required since they have unknown uncertainties, as discussed in chapter 11. Average values are calculated using external software. The collected data is not based on control signals but sensor data or estimations. The sensor types and positions in DS1 affect the result. The locations of the sensors are not known e.g. where the winding temperature is measured.

## 9.2 Interface

Both DS use a CAN interface for communication. CAN is a serial communication technology used especially for reliable data exchange between Electronic Control Units (ECUs). CAN is used in vehicles because it reduces the wiring effort, is reliable and enables high data exchange which is required in modern vehicles to control the powertrain to reduce emissions [41]. The basic CAN frame format is presented in Figure 32.

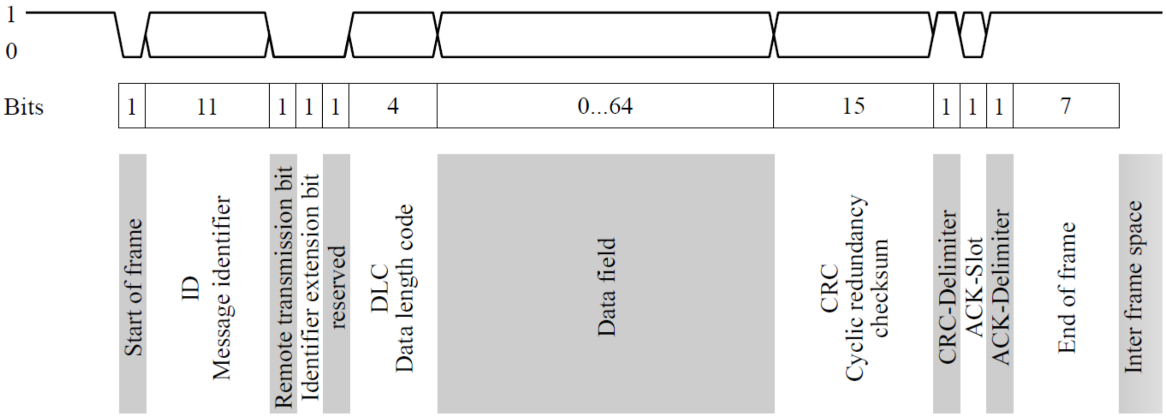


*Figure 32 CAN frame format [42]. With courtesy of Fröstel (S.G.).*

Test data received from the CAN is stored in Binary Logging Format (BLF). These files can then be transformed to a cell format for processing in Matlab. The cell format makes it possible to store different sizes of data, which is necessary to use the instruments as specified, e.g. the speed resolution is higher than for temperature.

## 9.3 Test procedures

This section states the desired test procedures for testing a DS on the Renault testbed, in order to obtain the parameters in Table 17. There are several test standards. In this project, an internal norm at Renault Trucks is used when possible.

All tests are performed in steady state. A system is in a steady state if the state variables that defines the system's behaviour have a derivative of zero. There is both fast and slow dynamics in a DS. The states to consider when testing a DS are electrical, mechanical and thermal.
The initial cooling temperature is set to 65°C since this temperature has been used in previous tests. It is important to check if external tests are performed as desired, and if not, how they can be used. A discussion about the following procedures and external tests is presented in section 11.2.1.

### 9.3.1 Max torque and power

- Tune inputs to nominal values.
- Preheat the DS with the cooling system set to 65°C.
- Wait for the winding temperature to stabilize.
- Set dynamometer torque to zero.
- Set DS SP to desired Operational Point (OP) speed with a margin of SP·10%.
- Run the DS until it reaches electric and mechanical steady state.
- Start measurements of parameters in Table 18.
- Increase the dynamometer torque using small steps or a ramp.
- Measure until the OP speed cannot be maintained within the margin.
- Repeat this process for other SP using a suitable increment, e.g. 500 rpm.

### 9.3.2 Sensitivity analysis

- Tune inputs to desired test values, e.g. cooling system temperature and source voltage.
- Preheat the DS using the cooling system.
- Use the same procedure as in section 9.3.1 except step 1 and 2.
- Repeat this process for other inputs.

### 9.3.3 Efficiency (at max power)

Measurements from the max torque and max power tests are used to calculate the efficiency.

### 9.3.4 Power loss at zero torque demand

Power losses at zero torque demand is the electric power the DS use to remain at a SP without any load. Two procedures to test power losses at zero torque demand are proposed:

Procedure 1

- Separate the DS from the axis to the dynamometer.
- Preheat the DS with the cooling system set to 65°C.
- Wait for the winding temperature to stabilize.
- Set SP to desired OP speed.
- Run the DS until it reaches electric and mechanical steady state.
- Start measurements of DS voltage and current, as stated in Table 18.
- Repeat this process for other SP

Procedure 2

- Change torque sensor between the DS and dynamometer to a sensor with a range of e.g. 10% of the DS rated torque.
- Preheat the DS with the cooling system set to 65°C.
- Wait for the winding temperature to stabilize.
- Turn on the DS. It is required since it has permanent magnets in the rotor.
- Set the dynamometer SP to desired OP speed.
- Run the dynamometer until the system reaches electric and mechanical steady state.
- Enable torque measurements, as stated in Table 18.
- Repeat this process for other SP.

In this project is test method 1 preferred since it can be used at the Renault testbed. Procedure 2 is assumed to be more accurate.

### 9.3.5 Derating time from peak to nominal power

A controller can realise a derating, as presented in section 4.4.4. In this proposed test is the derating time from peak to nominal power studied. The max boost time can also be determined using data from this test.

- Preheat the DS with the cooling system set to 65°C.
- Wait for the winding temperature to stabilize.
- Set the dynamometer speed to a SP.
- Increase DS torque demand to max torque at SP speed, as measured using procedure 9.3.1.
- Start a clock
- Wait for a derating to occur, that is a power drop.
- Wait for nominal power
- Stop the clock
- Repeat this process for other SP.

### 9.3.6 Torque map from Id and Iq currents

This test is proposed to determine the Id and Iq currents that gives MTPA. A control method using this test data is presented in section 4.4.3.

- Set up the frequency of the controller and minimum rise time $r_t$ for the current.
    - $r_t > 6 \cdot fs^{-1}$ is a rule of thumb for discrete time control systems.
- Preheat the DS with the cooling system set to 65°C.
- Wait for the winding temperature to stabilize.
- Run the DS without load to determine the back Electromotive Force (EMF).
- Use the back EMF to decouple the DS during proceeding test.
- Turn off filters, deadtime compensation etc.
- Set the dynamometers speed SP to a low value.
    - At zero speed is the DS heated uneven.
- Start to measure torque, Id and Iq currents.
- Set Id and Iq current values in controller as in the pattern defined in Figure 33.

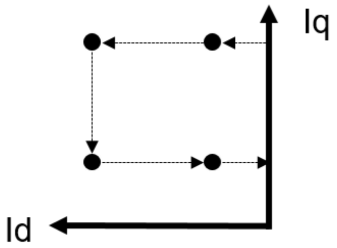


*Figure 33 Process to map torque as a function of Id and Iq currents by setting Id and Iq values in the DS controller.*

# 10 Results

In this chapter the results are presented from the simulations and verifications of the DS models and a sensitivity analysis performed on the DS1 model. The simulations, verifications and sensitivity analysis are described in chapter 6 and the DS in section 4.3. The verification uses simulations that imitate corresponding hardware tests. This means that only a part of the speed range is verified.

## 10.1 DS accuracy

The accuracy of a model is determined in a verification by studying a deviation between the measurements and model simulation. The measurements are regarded as true values with some uncertainty as described in section 8.2.

A deviation in percentage (prc) between measurements from tests and imitated tests in simulation are calculated in:

$$\mathrm{f}_{\mathrm{prc}}(w) = \frac{measured_{data}(w) - sim_{data}(w)}{measured_{data}(w)} \cdot 100 \tag{11}$$

As stated in section 6.1, the model is accepted if:

$$X_{prc} = \max\Big(f\big(w_{1,\ldots,n}\big)\Big) - \min\Big(f\big(w_{1,\ldots,n}\big)\Big) \tag{12}$$

Is less or equal to 10%, , $X_{prc} \leq 10\%$. The rpm deviation between a SP and a OP during simulation tests is < 2%.

DS1 and DS2 max torque in motor mode are tested using the procedure in section 9.3. Torque deviations $T_{dev}$ are calculated by substituting variables in (11) as:

$$T_{dev}(w) = \frac{T_{measure}(w) - \ T_{simulation}(w)}{T_{measure}(w)} \cdot 100 \tag{13}$$

Results from verifying the models using suppliers data are presented in percent in Figure 34 and in Table 19. Results from verifying the DS1 model using data from Renaults testbed are presented in percent in Table 19.

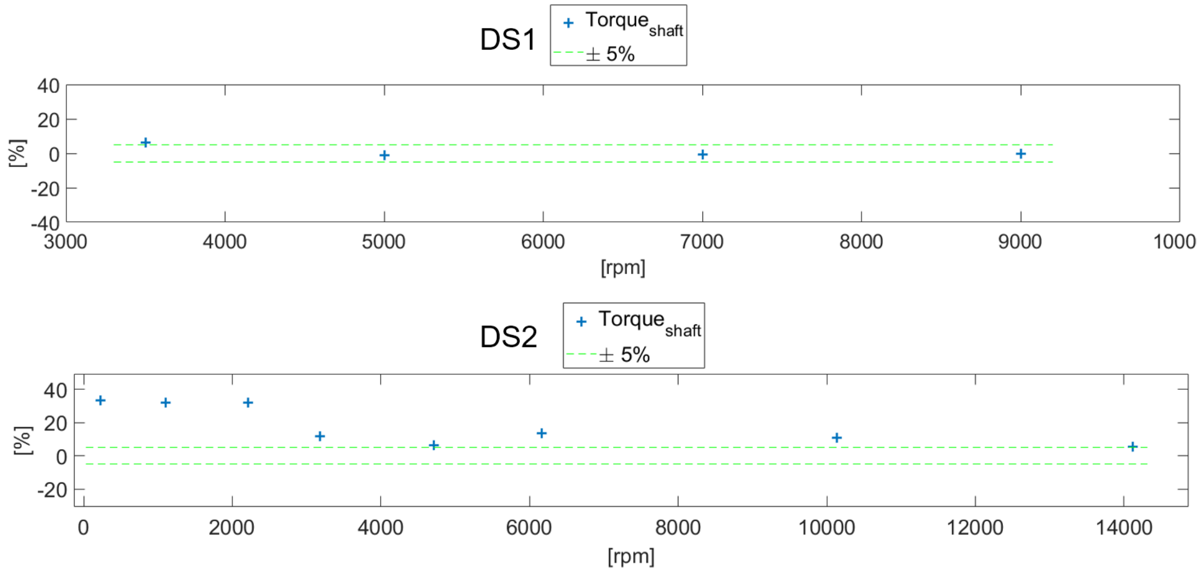


*Figure 34 Torque deviations between measurements from suppliers DS1 and DS2 tests and model simulation in percentage of the measured magnitudes.*

*Table 19 Torque deviations between measurements from DS1 and DS2 tests and model simulation in percentage of the measured magnitudes.*

| **DS1** | | | **DS2** | | |
|---|---|---|---|---|---|
| SP [$rpm$] | Deviation [%] | Test data | SP [$rpm$] | Deviation [%] | Test data |
| 398 | >10 | Renault testbed | 230 | 33.2 | Supplier |
| 911 | >10 | Renault testbed | 1100 | 32.1 | Supplier |
| 2513 | >10 | Renault testbed | 2200 | 31.9 | Supplier |
| 3500 | 6.5 | Supplier | 3180 | 11.5 | Supplier |
| 5000 | -1.3 | Supplier | 4700 | 6.4 | Supplier |
| 7000 | -0.7 | Supplier | 6160 | 13.7 | Supplier |
| 9000 | -0.2 | Supplier | 10130 | 11.0 | Supplier |
| | | | 14100 | 5.4 | Supplier |

DS1 and DS2 max power, provided to the shaft, are tested using the procedure in section 9.3. Power deviations $P_{dev}$ are calculated using:

$$P_{dev}(w) = \frac{P_{measure}(w) - P_{simulation}(w)}{P_{measure}(w)} \cdot 100 \qquad (14)$$

Results from verifying the models using suppliers data are presented in percent in Figure 35 and in Table 20. Results from verifying the DS1 model using data from Renaults testbed are presented in percent in table 20.

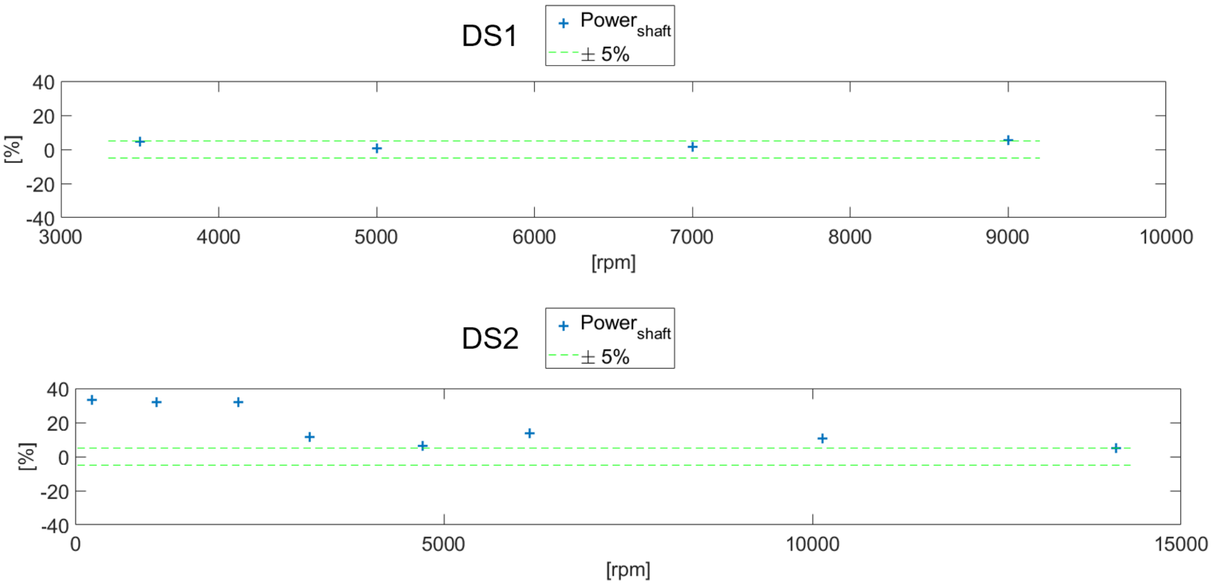


*Figure 35 Power deviations between measurements from suppliers DS1 and DS2 tests and model simulation in percentage of the measured magnitudes.*

*Table 20 Power deviations between measurements from DS1 and DS2 tests and model simulation in percentage of the measured magnitudes.*

| **DS1** | | | **DS2** | | |
|---|---|---|---|---|---|
| SP [$rpm$] | Deviation [%] | Test data | SP [$rpm$] | Deviation [%] | Test data |
| 398 | >10 | Renault testbed | 230 | 33.3 | Supplier |
| 911 | >10 | Renault testbed | 1100 | 32.0 | Supplier |
| 2513 | >10 | Renault testbed | 2200 | 31.8 | Supplier |
| 3500 | 4.4 | Supplier | 3180 | 11.5 | Supplier |
| 5000 | 0.5 | Supplier | 4700 | 6.4 | Supplier |
| 7000 | 1.6 | Supplier | 6160 | 13.6 | Supplier |
| 9000 | 5.6 | Supplier | 10130 | 10.9 | Supplier |
| | | | 14100 | 5.1 | Supplier |

DS1 and DS2 efficiency are tested using the procedure in section 9.3. Efficiency deviations $\eta_{dev}$, that is the ratio between shaft power and electric power, are calculated as:

$$n_{dev}(w) = \frac{n_{measure}(w) - n_{simulation}(w)}{n_{measure}(w)} \cdot 100 \tag{15}$$

Results from verifying the models using suppliers data are presented in percent in Figure 36 and in Table 21. Results from verifying the DS1 model using data from the Renault testbed are presented in Table 21.

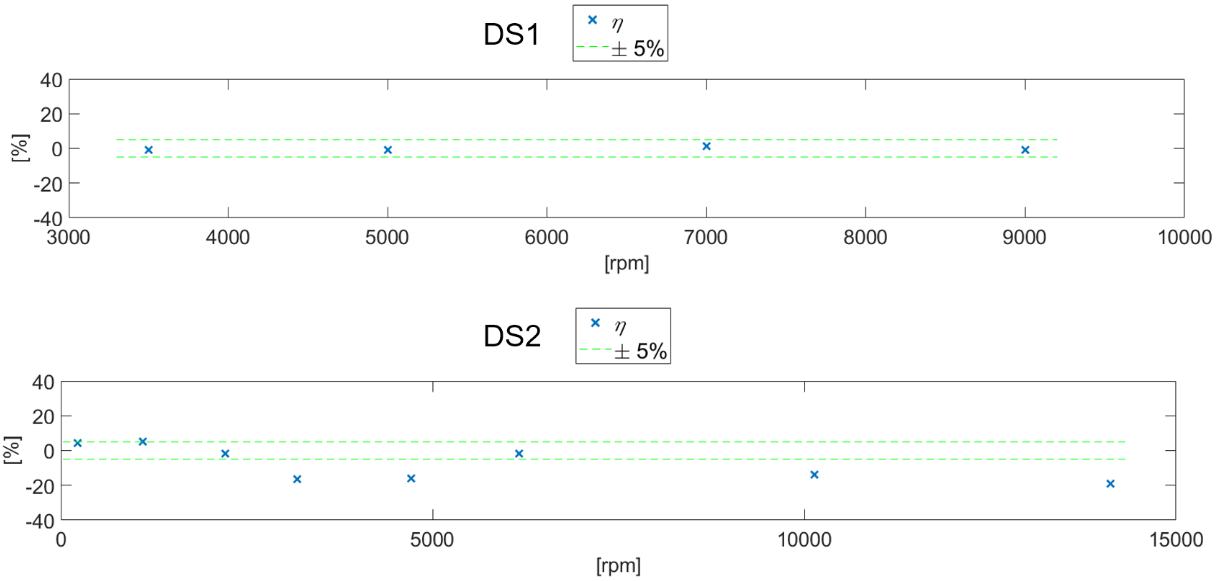


*Figure 36 Efficiency deviations between measurements from suppliers DS1 and DS2 tests and model simulation in percentage of the measured magnitudes.*

*Table 21 Efficiency deviations between measurements from DS1 and DS2 tests and model simulation in percentage of the measured magnitudes.*

| **DS1** | | | **DS2** | | |
|---|---|---|---|---|---|
| SP [$rpm$] | Deviation [%] | Test data | SP [$rpm$] | Deviation [%] | Test data |
| 398 | >10 | Renault testbed | 230 | 4.2 | Supplier |
| 911 | >10 | Renault testbed | 1100 | 5.1 | Supplier |
| 2513 | >10 | Renault testbed | 2200 | -1.6 | Supplier |
| 3500 | -0.9 | Supplier | 3180 | -16.5 | Supplier |
| 5000 | -0.7 | Supplier | 4700 | -16.0 | Supplier |
| 7000 | 1.3 | Supplier | 6160 | -1.7 | Supplier |
| 9000 | -0.9 | Supplier | 10130 | -13.7 | Supplier |
| | | | 14100 | -19.2 | Supplier |

DS1 and DS2 model power losses at zero torque demand are tested in simulation, using the test procedure in section 9.3. The losses are presented in percent of the DS power ratings. Simulation results from the test of the DS1 and DS2 model are presented in Figure 37 and in Table 22. If hardware tests are performed, the results can be used to study the accuracy of the models.

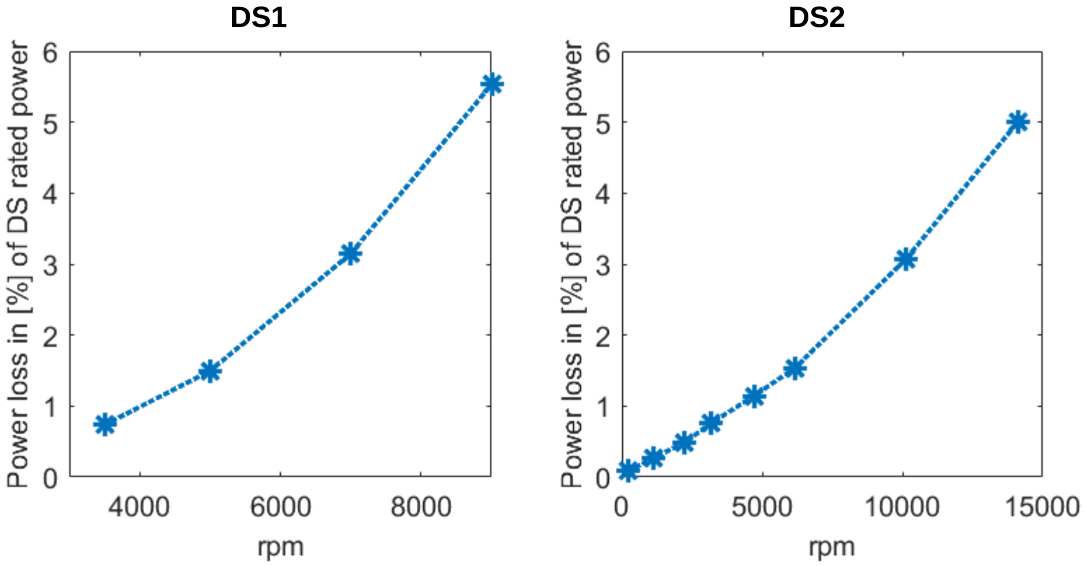


*Figure 37 DS1 and DS2 power losses at zero torque demand from model simulation in percent of their rated power.*

*Table 22 Power losses at zero torque demand from model simulation of DS1 and DS2 in percent of their rated power.*

| **DS1** | | **DS2** | |
|---|---|---|---|
| SP $[rpm]$ | Power loss in [%] of DS1 rated power | SP $[rpm]$ | Power loss in [%] of DS2 rated power |
| 3500 | 0.7 | 230 | 0.1 |
| 5000 | 1.5 | 1100 | 0.3 |
| 7000 | 3.2 | 2200 | 0.5 |
| 9000 | 5.5 | 3180 | 0.8 |
| | | 4700 | 1.1 |
| | | 6160 | 1.5 |
| | | 10130 | 3.0 |
| | | 14100 | 5.0 |

DS1 and DS2 model derating times from peak to nominal power and max boost time are tested in simulation, using the test procedure in section 9.3. Simulation results from tests of the DS1 model are presented in Table 23, where p-n is the peak to nominal time, as presented in section 4.4.4. The test results of the DS2 model do not show any derating. The derating parameters in the provided data are equal to 1, which means that the derating is not populated with values that represent DS2 deratings. If hardware tests are performed, the results can be used to study the accuracy of the models.

*Table 23 Derating time from peak to nominal power in simulation of model DS1 and max time in boost mode.*

| SP $[rpm]$ | p-n [sec] | Max boost time [sec] |
|---|---|---|
| 3500 | 1450 | 67 |
| 5000 | 1463 | 102 |
| 7000 | 1243 | 119 |
| 9000 | 1273 | 126 |

DS1 model torque, depending on the Id and Iq currents, is tested in simulation, using the procedure in section 9.3 adapted to simulation, where the speed is set to 250 rpm. The result is used to find the Max Torque Per Ampere (MTPA) in simulation. The Id and Iq combinations that result in MTPA are determined for rated torque and 75%, 50% and 25% of the rated torque as presented in Figure 38. The currents are given in per-unit of the current at rated torque. No accuracy is determined since there is not any hardware test data available.

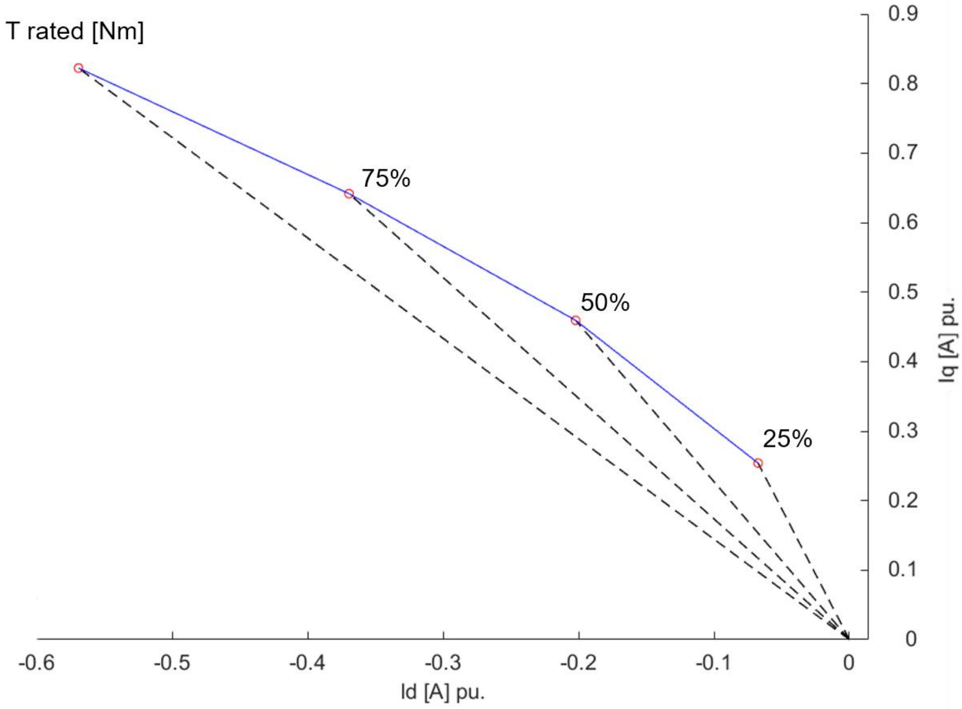


*Figure 38 DS1 model MTPA at four torque points where the currents Id and Iq are given in pu. of the current at rated torque.*

## 10.2 DS1 sensitivity

In this section, DS1 model sensitivity for cooling water temperature and voltage variations are presented. These parameters are of interest, as stated in the specification of requirements. A sensitivity analysis is performed in simulation according to the test procedures in section 9.3. The speed is set to 6000 rpm, since the DS often run at this speed.

### Cooling water temperature

The cooling water temperature at DS1 model inlet is varied around its nominal value 65°C in simulation. Torque deviations depending on the cooling water temperature from the nominal max torque at 6000 rpm are presented in Table 24. The DS1 model is turned off when the temperature is too high, as in the case before 105°C.

*Table 24 Cooling water inlet temperature variations and resulting torque deviations from the nominal torque, at 6000 rpm in simulation.*

| Cooling water [°C] | Max torque [Nm] | rpm |
|---|---|---|
| 65 | Nominal | 6000 |
| 75 | – 2% | |
| 85 | – 4% | |
| 105 | Coolant temp too high | |

### Voltage

The source voltage to the DS1 model is varied around its nominal value 48V in simulation. Torque deviations from the nominal max torque at 48V at 6000 rpm are presented in Table 25.

*Table 25 Voltage variations and resulting torque deviations from the nominal torque, at 6000 rpm in simulation.*

| Voltage [$V$] | Max torque [Nm] | rpm |
|---|---|---|
| 50 | 4.8% | 6000 |
| 48 | Nominal | |
| 46 | −7% | |

# 11 Discussion

In this chapter, the DS2 model and the results are discussed.

## 11.1 DS2 model

This section mainly discusses the criteria used to select subsystems.

The selection criteria are based on experience, new criteria can result in another implementation of the DS2 model. DS2 subsystems can be replaced with more accurate subsystems proposed in this thesis, if more information becomes available. The Rstd model has previously been selected to model a DS within Renault Trucks. The selection in this thesis confirms that the Rstd implementation is suitable for modeling a DS.

The verification deviations are caused by the data used in the model. The model itself corresponds to its tuned values with a deviation $\leq 10\%$.

## 11.2 DS data

This section discusses the data collected for verifications, with respect to test procedures, scope and uncertainties and their causes. The verification process is presented in chapter 6 and an overview is given in Figure 24.

### 11.2.1 Test procedures

This section discusses the test procedures.

**Project procedures**

This section discusses the test procedures presented in section 9.3 that are used in the project.

The test procedure to determine max torque and power can be modified. The DS torque can be set to max and the dynamometer to control the speed of the DS. This can make the tests more stable. This change can also simplify the virtual test and reduce the ripple in the simulation output.

The test procedure to determine the efficiency (at max power) use measurements from testing the max torque. This results in an efficiency that can be considered low, since the DS is not the most efficient at this operation condition, even if the DS temperature is low during the test. This use of data makes it easier to underestimate the efficiency of the system rather than overestimating it.

The test procedure to determine derating time from peak to nominal power is only used in simulation. It is helpful to define what the nominal power is, in this project is it when the torque derivative is close to zero after a derating. The derating is assumed to be due caused by high temperature in the machine windings, however in the vehicle industry, the inverter is often the weakest link in the system, due to cost factors.

**Suppliers procedures**

The test procedures used to test DS1 are explicit stated, but not for DS2. For DS1, there are differences between the supplier’s and proposed test procedures in section 9.3. A difference in the supplier’s test procedures might explain the deviation in the DS1 result. The maximum torque in the hardware test is determined by measuring the torque when the machine is loaded from high to low speed. The heat generated in the machine during the hardware and simulation tests may therefore be different, even if the model is accurate.

### 11.2.2 Hardware tests

This section discusses the tests performed on the DS1 and DS2 and measurements during the test. Data are not collected for all tests proposed in section 9.3. In general, more data are needed so that the mean values can be calculated and the outliers removed to reduce the uncertainties. Also, more knowledge about sensors and instruments and their location can reduce the uncertainties.

**Project**

Only the DS1 is tested at the Renault testbed according to the proposed test procedure to determine its maximum torque and power. Three data points that are assessed as valid are available. Due to the testbed setup, several uncertainties are introduced e.g. the torque is estimated using the current from the inverter. The measurements uncertainties can be reduced by placing a torque sensor between the DS and the dynamometer.

**Supplier**

The test procedures are described and resembles those used in this project. Two data sets from the suppliers' hardware tests are used in the verification, one for DS1 and one for DS2.

### 11.2.3 Software tests

This section discusses the simulation of DS in the virtual testbed. Both DS models are evaluated using the same functions in Matlab and Simulink. Two supplied datasets are used in simulation, one for DS1 and one for DS2.

The deviation from the verification, when using hardware test data from the Renault testbed, can partially be caused by the software. A function that interpret .BLF files that contain the measurement data, called *interpertBLF*, is not verified. The function can be verified using functions in CANAlyzer, a license is required. However, more test data is required to use the function as intended. This function is only used to interpret datasets from the Renault testbed.

When testing the max torque and power, a deviation in rpm is noticed in the virtual testbed. This is caused by a margin set in the simulation to perform the test as at a testbed. This reduces the accuracy in the results.

DS1 derating times are not verified. The trend in time from peak to nominal power, as well as the trend in max boost time can be due to several factors e.g. how the rpm affects the cooling of the machine.

A dataset is provided to populate the maps and constants in the model of DS2. The dataset only seems to represent the DS2 continuous operation. This can be causing the positive deviation, the hardware tests are performed for max torque and power, but the simulation give torque and power during continuous operations. More data are required to populate the DS2 model as intended. Such data is not available but can be collected at the Renault testbed. The model has constants to implement deratings, but they are not set to a representative value. This explains why no derating is observed when performing a derating test on the DS2 model. A efficiency map is included, but it is also assumed to represent the continuous operation, which results in the efficiency deviation. By using the Renault testbed, a dataset can be obtained to populate the DS2 model. After obtaining a dataset can the model be tuned. Then the model is better known than the data from the supplier, which means that the supplier's data can be verified using the verification procedure.

The DS1 battery current is not smooth. A Finite Impulse Response (FIR) filter with coefficients with a weight of 1 over a period of 1 second, using 20 samples, is used to smoothen the current. The filter is used in all virtual testbed simulations. It is preferable to setup the FIR filter as the instrument in the test, but this is not possible since the instrument is not known. The filter lag does not significantly affect the result as the changes are relatively slow.

The power losses at zero torque demand are included in both models and they are as expected but not verified. The power consumption is calculated as function of current and voltage.

The derating times was at first determined by using the temperature in the stator. However, a derating can occur in other parts of the system, before the derating temperature in the stator is reached. By monitor the DS power, it is easier to observe deratings. The simulation test is time consuming because a simulation time with margins is used, there is no other condition to stop the simulation. But the program still meets the specification of requirements.

## 11.3 Verification

In this section, the verification is discussed.

The requirement on a deviation $\leq 10\%$, which is presented in section 6.1, can be too strict. It is a major deviation if it is a pure electric vehicle, but it has a reduced impact in a hybrid vehicle, since it is not the only propulsion system. This means that the model of DS2 can be useful in several simulations where the fuel consumption is estimated. Although the model is not accepted in this project.

The datasets used for the verification are previously discussed. The calculations in the verification, which use these datasets, are performed in Matlab with high precision.

## 11.4 DS1 Sensitivity

In this section, DS1 temperature and voltage sensitivity are discussed.

The results are expected, a DS with a PMSM using FOC loses torque when the cooling water temperature rises or when the voltage drops. However, data from hardware tests is required to verify the simulations.

# 12 Conclusion

The aims were to develop and verify a model of DS2 and to verify and perform a sensitivity analysis on an existing model of DS1.

The project work model lead to a model of DS2 in the Rstd format.

Performed verifications of max torque, max power and efficiency at max power show the following deviations for each system, respectively:

- $DS1 \leq 10\%$
- $DS2 > 10\%$

Simulations in the GSP using the DS1 model can be used to make desired assessments, even if it is recommended that more data is gathered. Results from simulations using the DS2 model should not be used to make desired assessments.

The simulations of power losses at zero torque demand are expected and can be used to verify the DS1 and DS2 model. The simulations of derating times can be used to verify the DS1 model.

The sensitivity analysis of the DS1 torque output in simulation shows:

- $-2\%$ for a 10°C increment and $-4\%$ for a 20°C increment of the water coolant temperature, from a nominal temperature at 6000 rpm.
- 4,8% for a 2V increment and $-7\%$ for a 2V decrement, from 48V at 6000 rpm.

The sensitivity analysis shows that the DS1 has an expected trend in the simulation output when the input space is not arbitrary restricted.

The methods and tools developed in this project can be used to further study the DS models. In this project, the testing and verification of DS have been improved by developing procedures and new tools.

# 13 Future work

In this chapter, unsolved and unexplored issues are proposed as future work. Solutions to these issues can contribute to answers of the research questions. The main future work is to use and improve the methods developed in this thesis to verify DS models so they can be used in GSP simulations to secure fuel economy.

### Modelling

It is possible to add and evaluate more modelling methods when new ideas arise or change criteria in the selection process. The model of DS2 can be improved since it is not encrypted.

### Test procedures

The test procedures can be improved based on user experience and by comparison with other test procedures. In addition, more test procedures can be added for desired tests, such as transient behavior.

### Hardware and software tests

A study of Renault testbed's measurement uncertainties and how to reduce them can be performed to be able to collect more accurate data. The virtual testbed can be verified to make sure that it acts as expected when using other datasets. Also, DS with higher voltage as 600V systems can be evaluated using the methods.

### Verification

In this project, models of DS are verified so simulations that use these models can be assessed. In a future production, the idea of mass production will be of interest. The methods in this project can be adapted to verify that a DS meet requirements in a standard when producing trucks.

### Sensitivity analysis

The sensitivity analysis range can be increased, and more parameters can be varied.

### Other

Fuel cells are of increasing interest, and a similar thesis for fuel cells can improve testing and modelling of fuel cells for vehicles.
A model for a digital twin can be developed with the DS2 model as a starting point.

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# Annex

## I. Specification of requirements

# Specification of requirements

## Specification of requirements DS2 model

| | *Criteria* | *Unit* | *Target value* | *R/D** | *Verification* | *W*** |
|---|---|---|---|---|---|---|
| | ***Functions*** | | | | | |
| A | Model inputs | | | | | |
| A1 | Torque demand | [Nm] | | - | | |
| A2 | DC source voltage | [V] | | - | | |
| A3 | Water flow | [l/min] | | - | | |
| A4 | Angular velocity | [rad/s] | | - | | |
| A5 | EM water inlet temperature | [°C] | | - | | |
| B | Model outputs | | | | | |
| B1 | Torque | [Nm] | | R | Unit analysis | |
| B2 | Simulation time | [sec] | | R | Unit analysis | |
| B3 | Supply current | [A] | | R | Unit analysis | |
| B5 | Winding temperature | [°C] | | R | Unit analysis | |
| B6 | Heat sink temperature | [°C] | | D | | |
| B7 | Motor loss | [W] | | D | | |
| B8 | Inverter loss | [W] | | D | | |
| B9 | Transistor Temp | [°C] | | D | | |
| B10 | Id | [A] | | D | | |
| B11 | Iq | [A] | | D | | |
| B12 | Machine voltage | [V] | | D | | |
| B13 | Water outlet temperature | [°C] | | D | | |
| B14 | Performance | [Pa] | | D | | |
| C1 | Accuracy deviation from actual events | % | ≤ 10 | R | Correlation of model and measurements | |
| C2 | Stability | - | No errors | R | Repeated tests in Simulink | |
| C3 | Performance | [sec] | < 150% of mds_adv | R | Repeated tests in Simulink | |
| C5 | Supplier compliance and data | - | | R | Study agreements, Unit analysis | |
| C6 | Model support and adaption | - | - | R | Interviews | |
| J1 | Automatic model update | - | - | D | | 3 |
| J2 | Short setup time | - | - | D | | 3 |
| J3 | Easy to interpret | - | - | D | | 3 |
| | ***Modularization*** | | | | | |
| D | Controller | | | | Only MathWorks software | |
| | Machine | | | | Only MathWorks software | |
| | ***Support functions*** | | | | | |
| E1 | Transfer of data from test to model | | | | | |
| | ***Undesired functions*** | | | | | |
| F1 | Adaptions | | | | | |
| | ***Cost*** | | | | | |
| G1 | Not included in this project | | | | | |
| | ***Material*** | | | | | |
| H1 | Provided software and data | | | | | |

* Required/ Desired
** Weights
5 : Essential
3 : Important
1 : Irrelevant

## Specification of requirements DS verification

| | *Criteria* | | *Unit* | *R/D** | *Verification* |
|---|---|---|---|---|---|
| | ***Functions*** | | | | |
| A1 | Simulate a DS model in a virtual testbed that imitates a hardware test | | | R | Known data |
| A2 | Plot deviation between measured parameters from hardware and simulation tests | | | R | |
| A3 | Parameters to be verified or simulated in steady state | | | - | |
| - | Verification of max torque | Verification | [Nm] | R | |
| - | Verification of max power | | [W] | R | |
| - | Verification of efficiency (at max power) | | [%] | R | |
| - | Simulation of power losses at zero torque demand (Simulation) | Simulation | [W] | D | |
| - | Simulation of derating time from peak to nominal power | | [sec] | D | |
| G2 | Max angular acceleration | | | D | |
| G3 | Temperature sensitivity | | | D | |
| G4 | Voltage sensitivity | | | D | |
| G5 | Evaluation of measurement uncertainties | | | D | |
| G6 | Max time in boost mode before derating | | | D | |
| | ***Support functions*** | | | | |
| B1 | Interpret measurements | | | R | |
| B2 | CAN communication from test data | | | R | |
| - | | *Unit* | *Group* | *Bits* | *Startbit* |
| - | p_pwr | W | 0xE4 | 16 | 16 |
| - | q_pwr | VAr | 0xE4 | 16 | 32 |
| - | t_motor | degC | 0xE3 | 16 | 32 |
| - | t_power_stage | degC | 0xE3 | 16 | 48 |
| - | ibat | Adc | 0xE2 | 16 | 16 |
| - | ubat | Vdc | 0xE2 | 16 | 32 |
| - | is | Arms | 0xE1 | 16 | 16 |
| - | motor_spd | rpm | 0xE0 | 16 | 32 |
| - | motor_trq | Nm | 0xE0 | 16 | 48 |
| | ***Undesired functions*** | | | | |
| C1 | Adaptions | | | | |
| | ***Cost*** | | | | |
| D1 | Not included in this project | | | | |
| | ***Material*** | | | | |
| F1 | Renault Trucks testbed | | | | |
| F2 | Provided software | | | | |

* Required/ Desired

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# Improve Testing and Model Verification of Electric Drive Systems

Electric Drive Systems (DS) are evaluated as a component in future powertrains for trucks, to improve the fuel economy and reduce emissions. By using a model of a powertrain and a DS it is possible to assess how the DS affects the powertrain. This reduces the need of prototypes but presuppose that the model reproduces actual processes with accuracy. To create an accurate powertrain model is a complex task and the introduction of a DS adds even more complexity. Model verifications by testing make it possible to state the model accuracy, which facilitate assessments of simulations using the model. This motivate projects to improve testing and model verification of DS.

In this thesis, two electric Drive Systems, DS1 and DS2, and datasets from tests are used to verify a model of DS1 and DS2. Tests procedures, a model of DS2 and verification tools are developed. They can be used to facilitate assessments of simulations of DS models to improve fuel economy and reduce emissions of future powertrains.