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Multi-attribute balancing for fast charger design using system simulation

Florent Pasteur[1], Sana Loussaief[1]

Siemens Digital Industries Software, 19
bd Jules Carteret, 69007 Lyon, France,
florent.pasteur@siemens.com

Executive Summary

Electromobility expansion during the last years is leading to a considerable power of electric vehicle chargers [1]. Furthermore, a too important charging time for long distance travel may put the brakes on a wide adoption of electromobility. Hence, DC fast chargers and extreme fast chargers are key solutions to limit the charging duration. However, fast charging brings further challenges regarding the charger station lifetime [2] as well as the battery warranty compliance.

This technical paper presents how system simulation helps to address the multi-attribute balancing of a charging station to meet the required performance, assess the system reliability and lifetime while limiting the cost of the power electronics components as well as considering real operating conditions such as the battery charging limitation or a variable load condition.

Keywords: Grid Feeding inverter; system simulation; reduced order model; fast DC charger; dynamic power sharing; Battery.

1 Introduction

Fast DC charging stations can deliver high power directly to the vehicle's battery, which allows for faster charging times compared to standard charging stations. These stations can typically deliver charging speeds of 50 kW or more and specific advanced models can even supply charging rates of up to 350 kW. This means that a fast DC charging station can fully charge an electric vehicle's battery in 30 minutes only, depending on the battery characteristics and the charging strategy.

In contrast, standard charging stations typically deliver lower power levels, typically around 7-22 kW, and require several hours to fully charge an electric vehicle's battery. These stations are useful for slower, overnight charging, or for charging in locations where drivers plan to stay for an extended period.

The maximum charging speed is found by a combination of factors, including the charging station's output power, the vehicle's battery capacity and maximum charging rate, and the type of charging connector used. Higher power levels can result in faster charging times, but the battery's maximum charging rate and thermal management system can limit the charging speed.

Fast DC charging stations offer significant advantages in terms of faster charging times and increased range for electric vehicles, but there are also disadvantages to consider, including higher infrastructure costs and potential battery wear and tear.

In this paper, the section 2 presents a system simulation design method for charging station. The section 3 describes the 400kW fast DC charging station system, the adopted control strategy as well as a reduced order model for the vehicle Battery pack. The section 4 shows the system simulation results. Finally, the section 5 includes conclusions with directions for future work.

2 The system simulation model development workflow

This section presents a model-based development process for a charging station system simulation. The model includes the power electronic module and corresponding thermal management system.

The design goal of a fast DC charger is to achieve the best balance between different competitive or interconnected requirements to achieve the best overall performance. First, the design must supply the required power. This must be true in every climatic condition, and it constrains the cooling requirements of the system. Optimizing the charging station global efficiency is bringing competitive advantages on the operating cost of the charger. The durability of power components must be sufficient to ensure the required service time. And the cost of the product is also of a high importance.

At the first stage, various degrees of freedom are given to the designer to achieve those goals. Therefore, massive simulation is a key to take the right design decision at an early stage. The more efficient and fast the simulation process is, the easier the study to find a best design is.

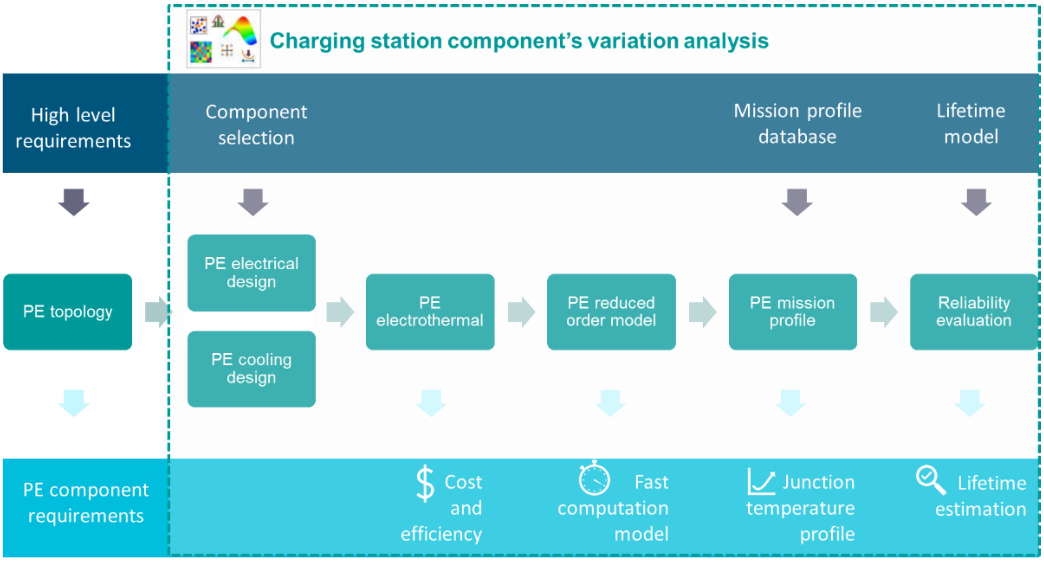

Figure1: Simulation driven decision workflow

The model development workflow consists in starting from the datasheet information to develop a detailed model of a liquid cooled 3-phase grid feeding inverter. This detailed model then is reduced to accelerate the computation time and run the simulation over a wide mission profile database.

The system simulation results over a fast charge simulation highlight the impact of the charging strategy, the climate conditions, the power component's technology, and the cooling system on the inverter junction temperature and hence the system reliability assessment.

The electric vehicle battery charging strategy is supposed to be a standard constant-current constant-voltage (CC-CV) [3] charging strategy.

3 Design by simulation and early evaluation of fast DC charging station attribute by system simulation

The fast DC charger architecture used in this study is a single AC/DC stage with a high-power rating used to form a common DC bus. A secondary isolated bidirectional DC/DC converters stage is connected to the common 800V DC bus to control the charging current of the battery. Two charging posts (CP) are available and enable dynamic power sharing to charge 2 vehicles simultaneously with optimal power distribution. The figure 2 shows this architecture:

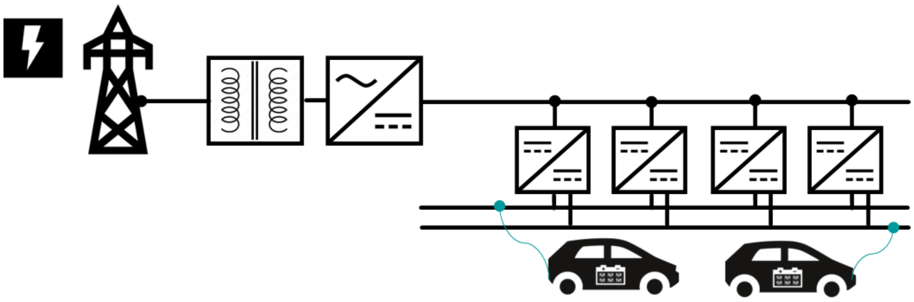

Figure2: Fast DC charger station overall architecture

The AC-DC converter of the first stage converts AC power from the grid into DC power which can be used to charge the vehicle's battery. This function is provided with a grid feeding inverter (GFD) [4]. The selected power component technology is high performance SiC power MOSFET.

The second stage DC-DC converter ensures to convert the 800V DC bus voltage to the appropriate voltage level for the vehicle's battery. This stage is made of 4 DC/DC converter units connected to the same 800V DC bus. They can be combined to enable dynamic power sharing for the two power cabinets. Two vehicles can simultaneously charge their batteries by allocating the optimal number of DC/DC converter units to each of them depending on each power cabinet power demand.

The power electronics module generates a significant amount of heat during operation. Hence, the model includes a liquid cooling system to dissipate this heat and prevent the components from overheating.

The fast DC charger station basic requirements discussed in this study are given in the table below:

Table 1: DC charging station requirements

	value
Maximum power	400kW
AC voltage	400V
DC bus voltage	800V
Maximum current	500A
DC battery voltage	200V – 900V

3.1 Grid feeding (GFD) inverter model

3.1.1 Dynamic switching modelling

The initial design step is to define a detailed GFD inverter model with the main inverter power component. The model considers the switching dynamic and conduction as well as the switching losses. The system power losses and characteristics are determined from the datasheet of the SiC power MOSFET module including temperature dependency. The model is set so that the switching losses are proportional to both the instantaneous AC current and DC voltage. The inverter PWM control switching frequency is 20 kHz. The

PWM control method is the DPWM1[5]. This PWM modulation strategy benefits of reduced switching operation for reduced switching losses. Figure 3 shows this GFD model.

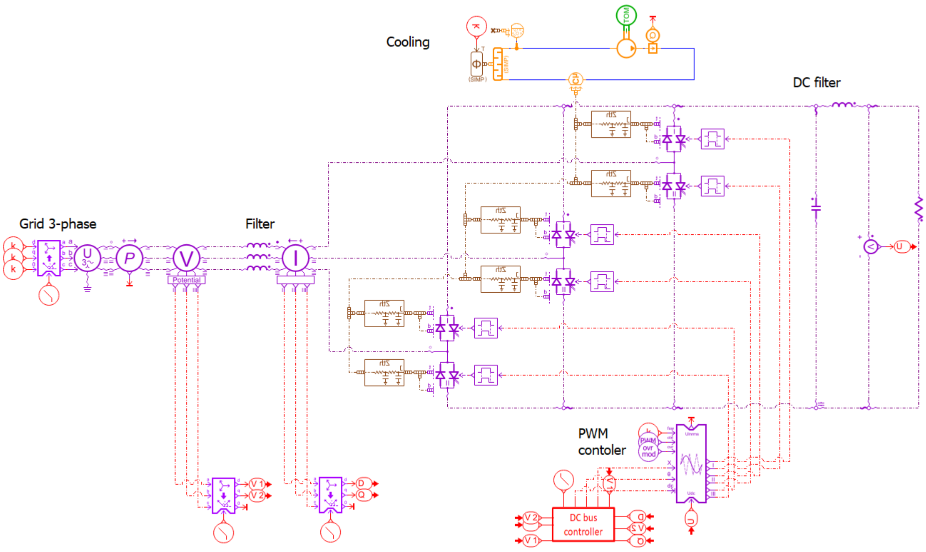

Figure 3: GFD model with switching dynamic assumption

This model is used as an initial design reference to validate component selection, to tune PI control parameter, to define power component cooling requirements, and to size and optimize the AC and DC filtering passive components. This initial design selection enables to assess GFD inverter global efficiency and to estimate the cost. Nevertheless, the simulation time is important, and this model is not very suitable for long simulation purpose. Typically, 4 seconds of simulation are simulated in 1 hour.

3.1.2 GFD DC bus controller

The control objective of the GFD is to regulate the common DC bus voltage to 800V. It is regulated using a PI controller outputting active power requirement. The reactive power objective is fixed to zero. The active and reactive power are converted into current objectives Id and Iq using the DQ0 transformation reference frame to work with constant DC quantities. The 800V DC bus current is controlled with a PI regulation which includes inductance compensation decoupling. See figure 4.

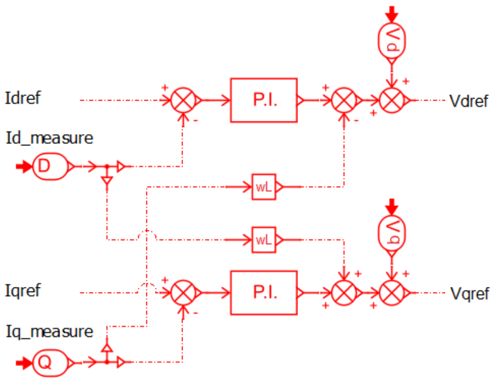

Figure 4: Current control loop of GFD inverter

3.1.3 Averaged switching

A straightforward simplification assumption is to consider average modeling for the PWM controller. The switching dynamic in this case is averaged, and the model's variables refer to the average of the real quantities. This assumption is valid thanks to the 20 kHz high frequency PWM which enables to neglect the current ripples. As a result, losses and temperature evolution remain almost identical as shown in figure 5.

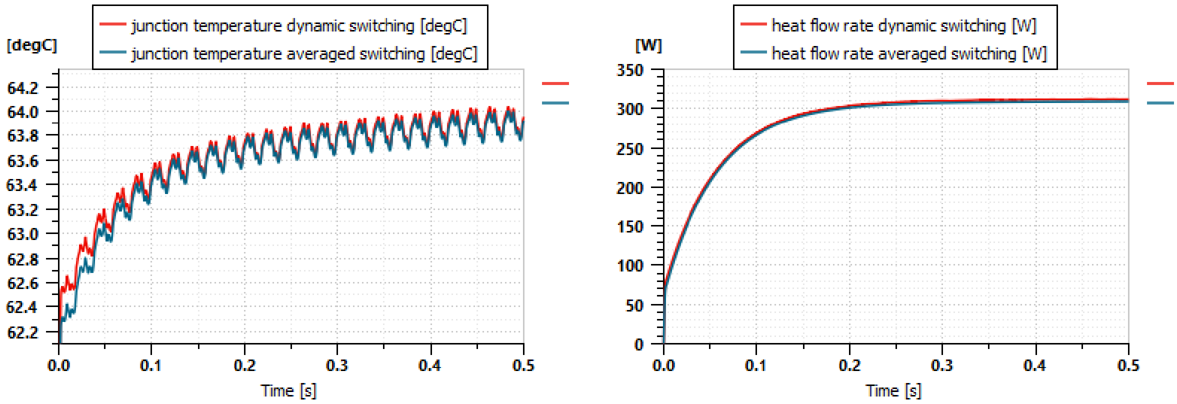

Figure 5: Temperature and losses comparison of switching dynamic and averaged model of the GFD.

This average switching model is used to generate a reduced model of the GFD inverter with fast simulation as explained in chapter 3.1.4.

3.1.4 Model reduction process for GFD fast simulation model

Despite the average model of the inverter reduces the simulation time, this level of details still requires important simulation time which does not fit long simulation run. The solution proposed in this paper is based on the detailed inverter model to set-up a model reduction process. We generate a quasi-static reduced model (QS model) which only considers the average quantities over an electrical revolution. The inverter model is reduced according to the 5 parameters given in table 2. All those parameters will be considered as constant over an electrical revolution.

Table 2: GFD inverter dependency

	range
DC bus voltage	700 .. 900 V
RMS voltage command	0 .. 1
D axis current	-1000 .. 1000 A
Q axis current	-1000 .. 1000 A
MOSFETs temperature	25;125;175

For each of those 25000 parameter combinations, simulated in batch with the Simcenter Amesim [6] Design Of Exploration (DOE), the total inverter losses is measured to create a 5D look-up table which characterizes the set of possible GFD operating conditions. Thanks to the averaged switching model assumption and parallel processing capabilities of the DOE this model reduction process takes about 20 minutes on a standard laptop with 15 parallel jobs.

Once the reduced GFD model is ready, the simulation performance analyzer indicates that the simulation dynamic is dominated by the 3-phase filter of the grid. To further improve the calculation time, the 3-phase grid network model with abc current state variables is replaced by a model based on the Park DQ0 transformation on the grid rotating frame. In this rotating frame all the sate variables become constant values at steady states operation. Finally, the obtained GFD inverter reduced model which is based on look-up tables is more suitable for system simulation with a simulation time divided by a 10^6 factor while keeping an accurate electro/thermal dependency of the system (figure 6).

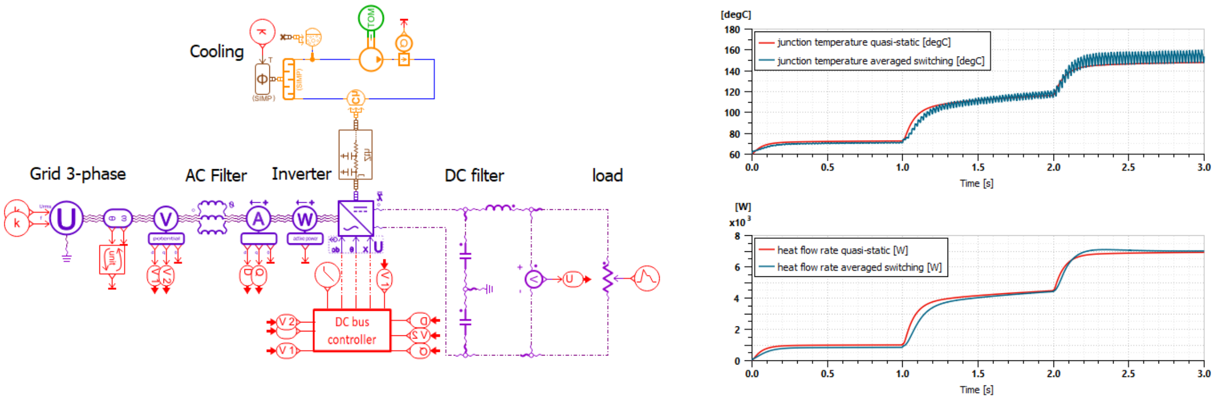

Figure 6: Left QS model of the GFD. Right: T° and losses comparison of averaged and QS model.

With this QS model assumption, long cycles can be simulated in acceptable CPU times (typically 1s to simulate 1000s). It is possible to consider the overall electro/thermal dependency of the system thanks to the association of the chips thermal model as well as the semiconductor characteristics which includes switching losses, as a function of temperature.

3.2 GDF cooling loop model

The GDF includes an integrated liquid cooling technology. The 6 MOSFET are stuck on a cold plate which is cooled by a liquid refrigerant at 60°C. The junction temperatures of the 6 MOSFET are calculated by a 1-node Cauer thermal model [7]. The latter can be obtained from test measurements or from the datasheet. In this power module, there are no separated diodes, therefore, the transistor function and the diode function are ensured at the same junction. Thus, the transistor, and the diode thermal ports are connected to the same Cauer thermal network with identical junction temperature hypothesis. The QS cooling loop model is identical to the dynamic one. The only assumption considered is the following: The 6 power MOSFET have the same temperature. Hence, there is one single Cauer model which takes as input the total inverter losses where the thermal resistance parameter is divided by 6.

The figure below describes another workflow to accurately simulate the MOSFETs thermal behavior while ensuring a fast computation time. This workflow will be adopted in a future work to improve the thermal model.

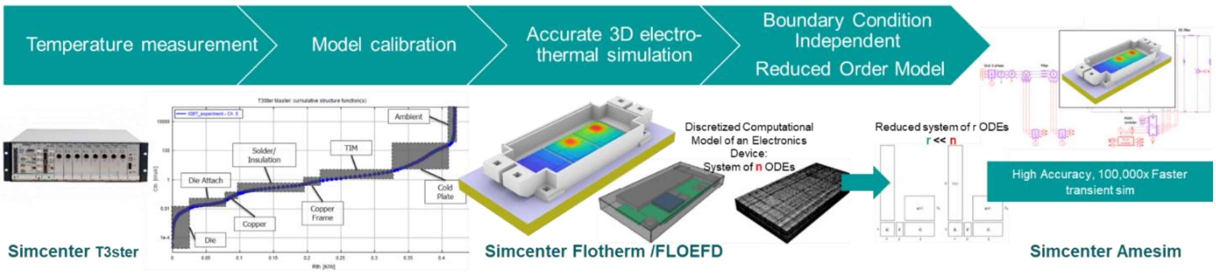

Figure 7: MOSFET Thermal simulation workflow from test to 3D Multiphysics till ROM and system integration

3.3 DC/DC converter model

A similar process as the one depicted for the GFD subsystem is conducted to get a model of the DC/DC converter stage. During this study, we focused on the analysis on the GFD, and functional DC/DC converter models have been used with global lumped parameters to define their efficiency.

Table 3 is giving the connection rule of the 4 DC/DC converter depending on the 2 charging posts power requirements:

Table 3: connection rule of the 4 DC/DC converter

CP1 power demand	CP1 power demand	DC/DC 1 connection	DC/DC 2 connection	DC/DC 3 connection	DC/DC 4 connection
>100 kW	>100 kW	CP1	CP1	EV2	CP2
>100 kW	<100 kW	CP1	CP1	CP1	CP2
<100 kW	>100 kW	CP1	CP2	CP2	CP2
0 kW	>10 kW	CP2	CP2	CP2	CP2
>10 kW	0 kW	CP1	CP1	CP1	CP1
0 kW	0 kW	off	off	off	off

This power distribution function is defined with a state chart model. It monitors the power requirement of the 2 charging posts every 10s to continuously rearrange the power distribution of the 4 DC/DC charging modules.

3.4 Battery CC-CV controller

The charger is controlled by the vehicle requirements of the CC-CV charging strategy to ensure a save charging. It applies a constant current until the battery reaches a predefined voltage potential. Then, this voltage is held constant and the current decrease until the battery is fully charged. Additionally, a thermal derating law is applied to limit the battery temperature within the safe range (Figure 3)

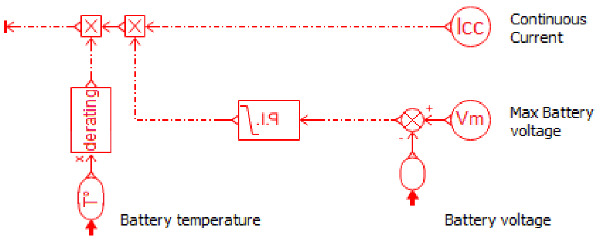

Figure 8: battery CC-CV controller with thermal derating

3.5 Battery pack Reduced Order Model

3D Multiphysics modelling approach is a helpful solution to predict the battery pack hot spots during a fast charge scenario. Indeed, this method allows for 3D geometry consideration while solving the conjugate heat transfer and the battery pack thermo-electrical model.

However, with this modelling approach, the computation time is not suitable to run live tests including the charging station model and the controls.

In this section, we detail the workflow to develop a reduced order model for the battery pack starting from a detailed 3D Multiphysics model. The reduced order model is a hybrid model which includes both Artificial Intelligence and System simulation modelling approaches.

The battery pack reduced order model will be integrated to the fast DC charger station model in a future work.

3.5.1 3D Multiphysics result selection

The first step is to define which 3D Multiphysics details we want to keep while ensuring fast computation time during the simulation.

In this use-case, we want to keep predicting the following 3D Multiphysics results from Simcenter STAR-CCM+ [8] which is a Multiphysics computational fluid dynamics software:

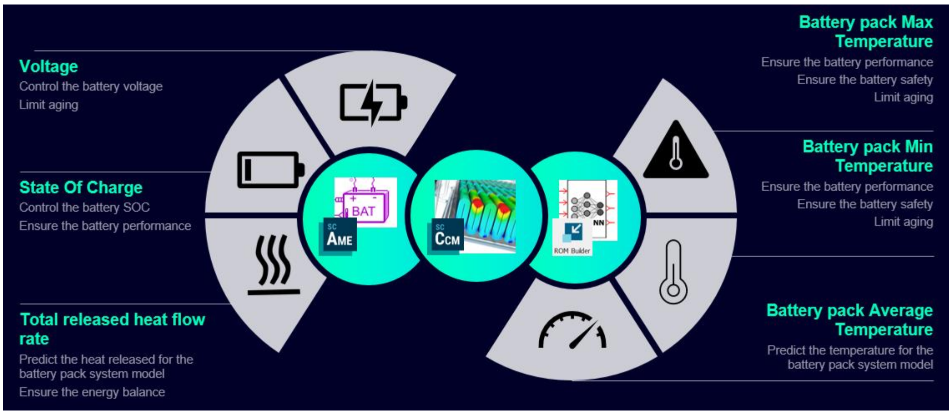

Figure9: List of the 3D Multiphysics results from Simcenter STAR-CCM+ to predict in the ROM Model

3.5.2 The AI model development workflow

The three steps to ensure an accurate Artificial Intelligence model are the followings:

First, we need to determine the Artificial Intelligence model inputs and outputs. We already know the outputs from the previous step which are the battery maximum, minimum and average temperatures.

From the other side, the inputs are the variables to which the outputs are sensitive: the current, the coolant mass flow rate, the coolant temperature as well as the voltage.

Second, we need data for the model training and validation purpose. Hence, we ran six fast charging simulations with different boundary conditions for the cooling system using Simcenter STAR-CCM+.

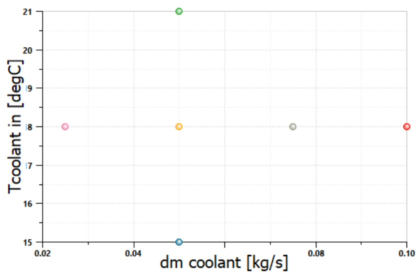

Figure10: The different boundary conditions used to generate the dataset

Finally, to develop the Dynamic Neural network model, we use the Simcenter ROM builder which is a general-purpose model order reduction tool [9]. The training and the validation fidelity shows respectively 99 and 98%.

3.5.3 The system model development workflow

To predict the voltage, the state of charge and the heat released by the battery pack, we use a Simcenter Amesim equivalent circuit battery model [10]. This model is connected to the neural network model generated in the previous step as illustrated in the figure below.

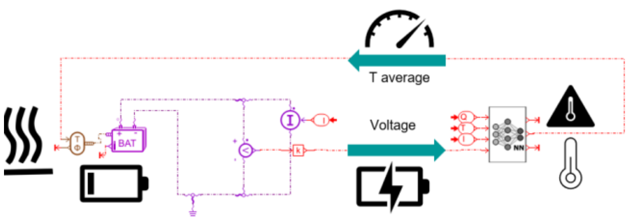

Figure11: The hybrid reduced order model integration

3.5.4 The battery reduced order model validation

The figure below shows the model fidelity against the 3D Multiphysics results. The average validation error is 99,2% .

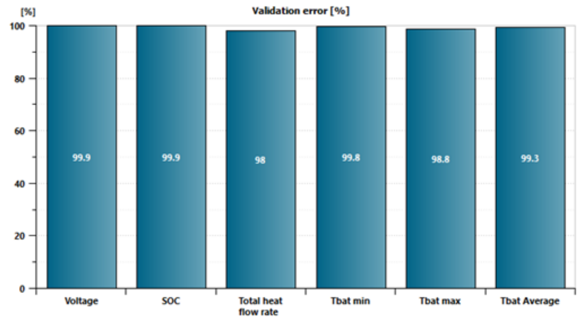

Figure12: The Battery reduced order model fidelity

On the other hand, the computation time is 0,04 seconds for a 2200s fast charge simulation. Consequently, this reduced order model offers fast computation time while preserving an extremely high accuracy.

3.6 Fast DC charging station overall model

The figure below shows the assembly of the different subsystems of the fast DC charging station.

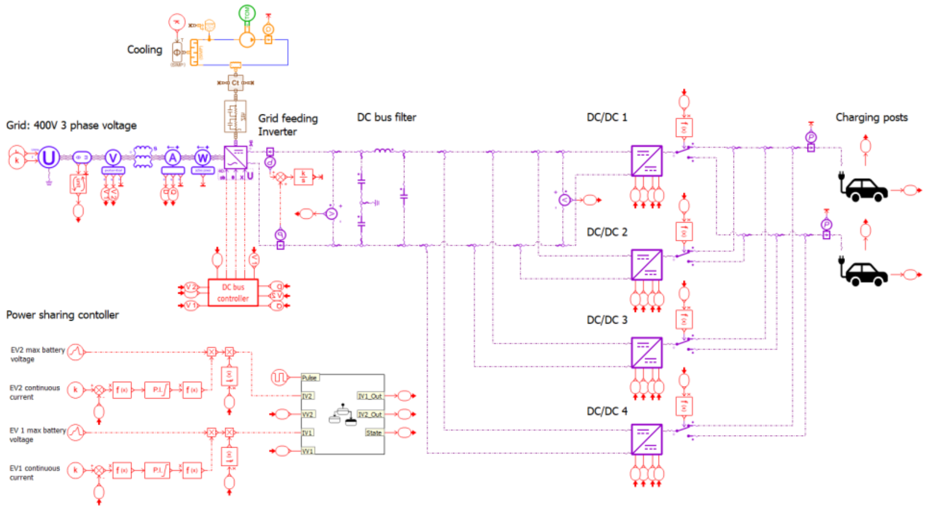

Figure 13: Fast DC charger station overall model

Beside the GFD system, the fast DC charging station model includes the 4 DC/DC charging module capable to deliver a power of 100 kW each. The power sharing control module receive as an input the electric vehicle charging requirements from the two charging posts. Based on those dynamic power request, the 4 DC/DC charging modules are reconnected continuously to the two charging posts for optimal and fair charging power splitting (chapter 3.2). A battery electro-thermal model is connected to each of the two charging posts. The parameters of those 2 battery electro-thermal models are obtained from the Simcenter Amesim "Pre-calibrated Tool for Battery" [11]. This comprehensive battery database enables to define different voltage battery class, with the relevant battery chemistry used for old and recent electric vehicles. It enables to make the simulation more realistic with the possibility to define typical battery performance on the actual electric vehicle market share, but also to create battery model for the upcoming 800V battery technology.

4 Results

We discuss in this section the main results obtained for the fast DC charging station simulations.

4.1 dynamic switching model of the GFD

Once the model architecture of the GFD is defined as explained in chapter 3.1.1 and 3.1.2, the dynamic switching model enables many simulations iteration to better design the GFD. First, we tune the power controller parameter based on initial design guesses. We can then adjust accurately the passive component size to ensure the GFD is accurately outputting the DC bus voltage and AC grid current within the specified distortion tolerances. This model also helps to define the appropriate performances and cooling requirements of the main power components. The filtering capacitor output current at maximum load defines the heating constraint requirements of the capacitance. The GFD total MOSFET losses is considered as a cooling requirement for the cooling system specification. The AC grid inductive filter size is optimized according to the maximum allowed current ripples and distortion. The figure below shows the main results regarding the system performance.

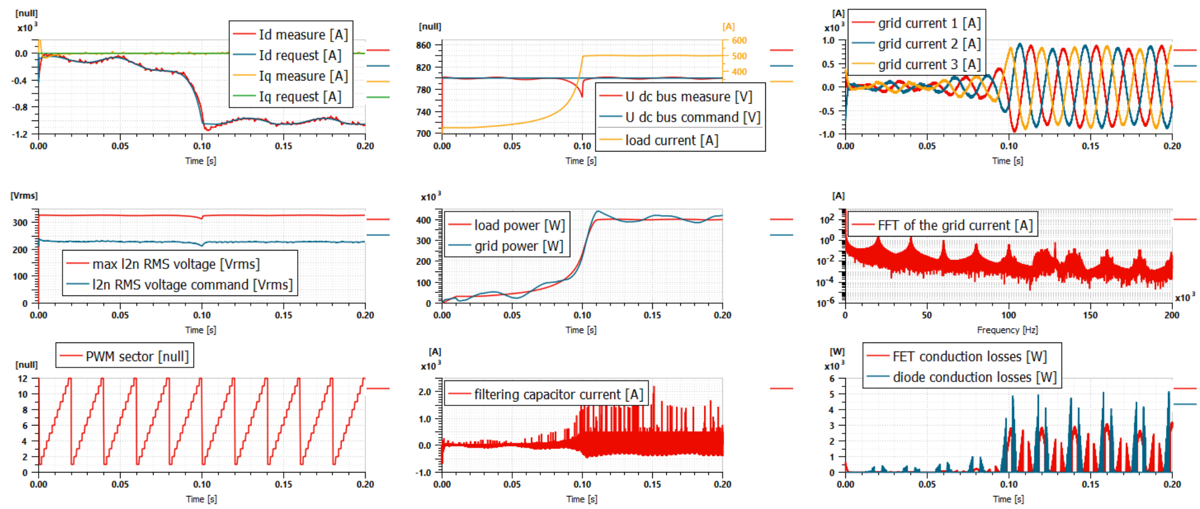

Figure14: GFD inverter main results. Left – monitoring of the main control quantities. Middle – monitoring of voltage current and power from 0 to max load. Right – monitoring of grid current quality and inverter losses.

Based on this initial detailed design requirements, we can estimate the cost of the GFD. Moreover, the efficiency under different operating conditions is evaluated as higher than 98% in any load condition. (Figure 15)

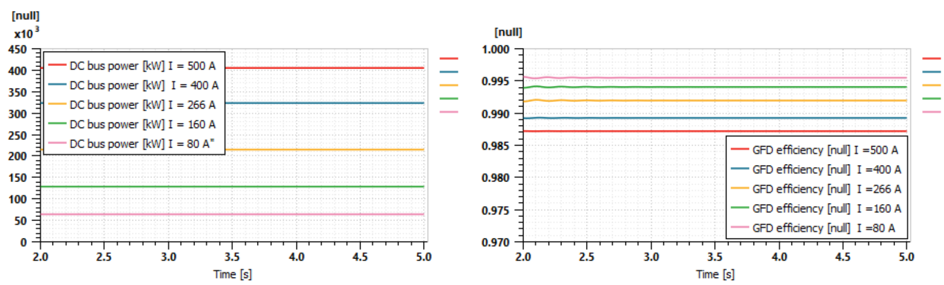

Figure15: GFD power and efficiency at different load current.

4.2 Quasi static model of the fast DC charging station

The quasi-static (QS) model of the fast DC charging station discussed in chapter 3.5 enables extremely fast simulation. Typically, the simulation time for 1 hour of real-life simulation only lasts 5 seconds. Compared to the dynamic switching model, it represents an increase of the simulation speed by a factor 10^6. Obviously, there is less accuracy in the results we obtain, but the QS temperature evolution of the GFD and the power flow along the different subsystems are assessed accurately by averaging the high frequency behaviour. The figure illustrates a typical simulation results for a scenario with a 400V vehicle connected to the CP2 for 4000s and a 800V vehicle connected to the CP1 from 1500s to 3000s .

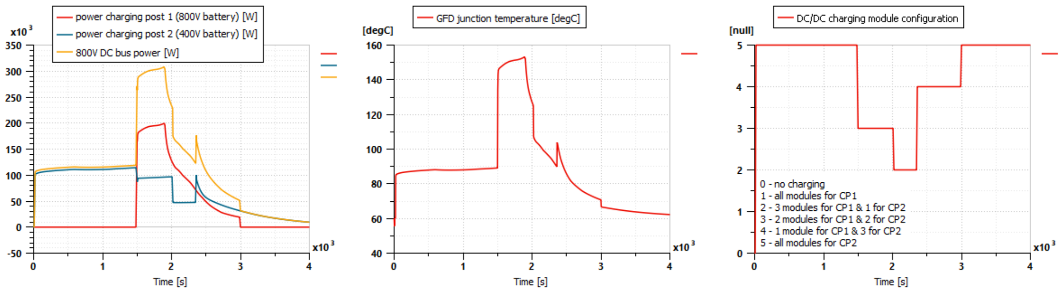

Figure16: fast DC charging station power and temperature for a given solving scenario.

This individual scenario can be replicated as many times a variation analysis is needed. For instance, we can study the impact on the GFD temperature for different battery configurations, different charging time, charging power, charging starting time, battery initial state of charge and temperature… The global temperature evolution for this large variety of charging scenario with dynamic power sharing can be easily evaluated with batch solving. At the same the parallel processing capabilities are leveraged . In the figure below, the result of a batch solving for different charging start time, charging duration, power requirement of the 2 charging posts is displayed.

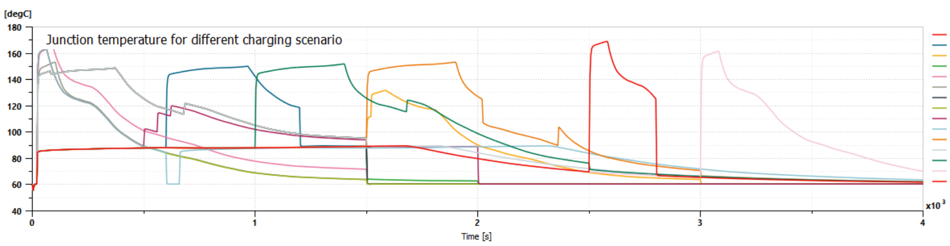

Figure17: GFD junction temperature evolution for several load case scenario.

This possibility to generate reliable and realistic mission profile helps to assess the power component reliability and lifetime for different expected service usage of the fast-charging station [1].

This QS model enables also to calibrate, optimize, and validate the power sharing controller of the fast DC charging station controllers.

It is worth to notice that as soon the simulation process has been set-up once, any change on the fast DC charging station can be easily updated, and the complete simulation process can be repeated quickly. A typical usage is to explore different subsystem configurations. The latter allows to determine the optimal charging station design for a given mission requirement at an early stage. Moreover, during a latter design stage, the model is updated according to any configuration change, allowing a fast validation. Finally real time target export can be used for SIL or HIL validation.

5 Conclusion and perspectives

This work shows how a model-based development process can support the design cycle of a fast DC charging station with multiple modelling level dedicated to specific simulation objectives. From high level requirement a first step is to simulate high fidelity simulation dedicated to the detail design and subsystem specification of the charger. Based on this detailed reference model, a reduced order model is built for realistic service life evaluation of the charger. This reduced model fully considers the electro/thermal dependency of the system and enables accurate evaluation of the power component temperature evolution. This temperature evolution according to realistic and comprehensive load case scenarios can be used to assess the power component reliability and lifetime.

A model for the DC/DC charging modules is under development. It includes the similar workflow than the one conducted for the GFD inverter in this work. The goal is to include the DC stage reduced model to the overall QS simulation model.

Another ambition is to include local power sources such as solar panels and electric energy storage system to the 800V DC bus. Such a model will make it possible to analyse and optimize the electrical cost of the charging station.

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Presenter Biography

Florent Pasteur is graduated in numerical science from Joseph-Fourier university in 2003. Then he worked as application engineer for a French electromagnetic finite element software company. He joined in 2011 the Simcenter Amesim team in Siemens Digital Industry Software. He has since been responsible of the product management of the Amesim Electric Motors and Drive solution.

Sana Loussaief is Business Developer for System simulation activities, supporting Vehicle Electrification applications (electrical motors, drives and batteries). She received a process engineering degree from ENSIACET Toulouse as well as a Master Diploma in fluid dynamics, energy and transfer from INP Toulouse in 2011.