Multiphysics Design and Analysis of Electric Vehicles

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Content

Summary

It is expected that over the next 10 years the number of new xEV models will increase significantly and with that the need to design more efficient vehicle systems with higher range and lower cost. With increasingly stringent regulations on emissions, safety regulation and the need to design complex interdependent systems such as e-machines, battery packs, power electronics, radiators, engine surface, and exhaust system. It has become critical to model the drive-train in its entirety especially the thermal management system (TMS). In this paper we would like to address how simulation would assist in minimizing the research, analysis, and experiments to analyze the complete behavior of vehicle systems to include where there is a need for strongly coupled resolution of flow, heat transfer, electromagnetics, electrochemistry, aging and stress during operation to provide the best possible prediction to maintain the integrity.

This paper presents a case study for an EV based SUV, which considers the battery and e-machines's multiphysics aspects of - electrochemistry, thermal and electromagnetics and thermal mechanisms respectively. The present work implements 1-D and 3-D unsteady simulation for the battery pack. The cell is characterized and then the pack level cooling is developed to achieve the required range based on a WLTC drive cycle. This is followed by electric machine analysis to obtain the magnetic field and loss distribution and exchange the data with the full 3D CFD thermal model. Finally looping in radiator coolant loop, power electronics, air conditioning with e-machine and battery coolant loop for thermal comfort. All the above individual components can be connected in one environment of Simcenter STAR-CCM+ linked by the new feature Simulation Operations, which eases the linking of multi-physics simulations significantly and simulating the TMS.

In all, it is becoming more vital to analyze the entire vehicle through simulation to capture the Multiphysics complexity not only at the component but also at the vehicle level as it a multi-attribute problem.

1 Introduction

Vehicle Thermal Management is highly important for electric vehicle (EV). In general, the performance of the vehicle is greatly depending on how warm or cool it is besides scenarios of overheating that can also be a severe safety concern [1].

Thermal management is vital to ensuring new vehicles to meet great vehicle range on a single charge. However, it is not just the battery pack that needs performance studies. Other electrical components including inverters and e-motors also to be considered. As with many areas of the vehicle, simulation can play a useful role to provide an approach to evaluate combined heat loads under a wide range of operating conditions. Another key factor that Thermal management address is serious fire-related incidents. The causes of these fires have varied with poor thermal design allowing batteries to overheat and in other contaminants in the cells being the cause in some cases. Operating an EV battery within the range of its operating temperature can help to preserve its capacity, reduce the thermal resistance of the battery, achieve even higher fast charging rates and better cooling performance, optimize its length of charge and retain the state of health of its cells and in turn pack. For EV Electrical Machine maintain it below a certain temperature as one needs to avoid hotspots in the magnets and winding as that will results in faults which would be unfavorable for longevity of vehicle.

In order to accommodate various drive cycles, designing a cooling system plays a crucial role in defining vehicle driving performance, operational limits and thermal comfort. With the help of Vehicle Thermal Management, we can model the heat losses and calculate the temperature of the power electronics. Ensuring that drivers can cool or heat the ambient temperature of the cabin without impacting driving range is vital, but this can pose a challenge for thermal management. Hence Thermal management simulations can improve powertrain and passenger comfort system efficiencies and are also important for the implementation of powertrain technologies. Therefore, it requires deep analysis of both temperature and thermal loading compatibility between systems.

2 Traditional Vehicle Thermal Management (VTM)

The importance of vehicle thermal management system is to enhance the vehicle thermal performance, as well as to achieve passenger comfort and maintaining component durability. In a conventional vehicle (ICE), designing a vehicle engine cooling and under-panel a heat protection from exhaust system is very vital at the early design concept level of vehicle development is common practice using CFD. Over the past two decades, the role of numerical analysis in every OEM has become mandate to validate the design virtually. Effective performance radiator defines the vehicle’s cooling system under various drive cycles. which heavily depends on the flow of ambient air passing through it. Traditional vehicle thermal management studies aim to predict front end airflow, heat exchanger performance, front grill & bumper opening area, size of fan and radiator and Thermal behavior.

This kind of performance study results are used to improve the effective heat protection systems around major heat sources such as the exhaust manifold and pipe. An accurate prediction of heat transfer between fluids and solids those are of different time scale is a demanded simulation focus especially, at Idle and key-off (Thermal Soak) transient. This is indeed to extract time varying thermal behavior of solid components those are exposed to high temperature because of lack of convection airflow. The results are then validated with test data.

3 Electrical Vehicle Thermal Management (eVTM)

The goal for the eVTM is similar to the ICE vehicles (ICEV) i.e. to achieve passenger comfort, maintaining component durability and in addition maintaining range of the vehicle. We are seeing advanced approaches to VTM to increasing range while maintaining passenger comfort. The difference between the thermal management approaches for ICEVs and EVs lies in difference of energy source, powertrain architecture and HVAC system [2]. The energy of propulsion in ICEVs comes from the combustion of fossil fuels and in regard to EVs, this energy is provided by electrical machine acting as generators and saving energy in batteries instead of ICE [4]. The elimination of waste heat generated from ICE but the combined advanced thermal management challenges of electrified powertrain from batteries, eMachines, power electronics for reduction of thermal load reduction and enhancing passenger comfort in EVs.

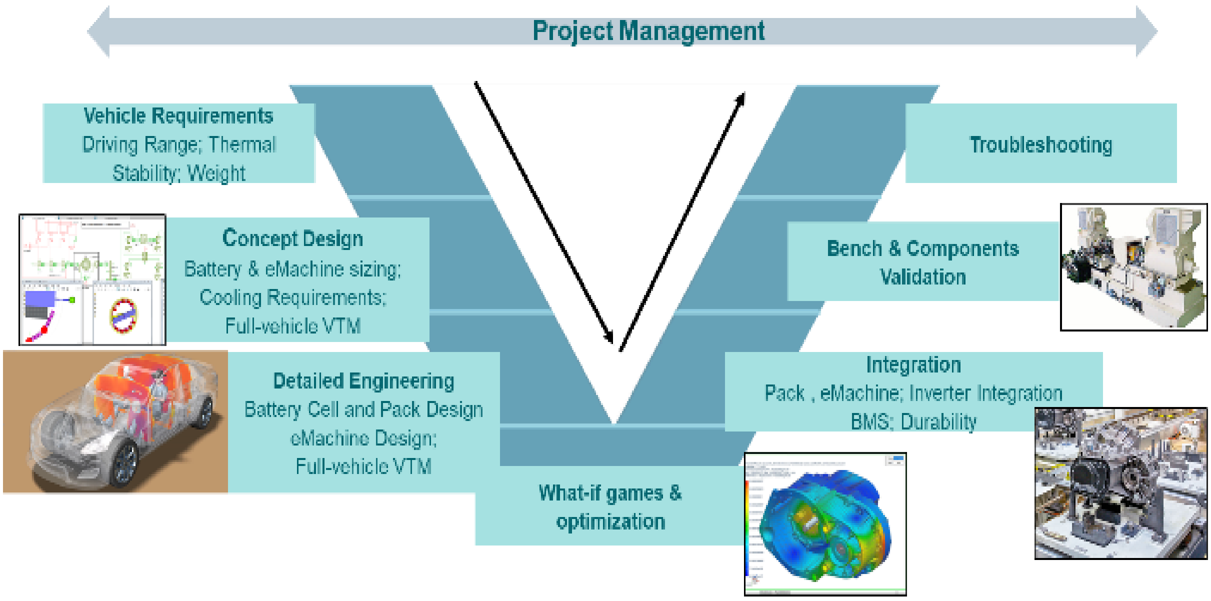

Fig. 1 Project Management of Electrical Vehicle Development V-Cycle Process

The EV design process usually follows a V cycle as shown in Figure 1. The system level requirements can be translated to requirements for concept and then detailed stage in the V cycle to create a digital twin of various components and system. Design exploration or performing what-if analysis is then performed to improve the material usage at component and/or system level. The various components are then integrated in the system level design to validate the design based on initial vehicle requirements. If there is gap in results to requirements, then design is improved and evaluated. This entire V-cycle process creates a digital twin. A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart's performance characteristics. Digital twins are used throughout the product lifecycle to simulate, predict, and optimize the product and production system before investing in physical prototypes and assets [5]. These requirements can be used to validate the virtual test bench criteria, essentially to prevent temperatures of the eMachine and pack from exceeding permissible level and improve the temperature uniformity of different cells in the module.

Tradition ICEVs produces additional mechanical power to drive water pump, compressor and other heat dissipating components to control the temperature of engine and cabin. Different from ICEVs, For EVs, although they are highly power efficient and relatively lower heat generating rate but are the highly sensitive to temperature fluctuations and maintaining low operating temperature range of these eMachines, batteries, power electronics components require that the thermal management system must have quick real-time response to the vehicle driving condition as the losses increase significantly hence, the thermal management of electrified powertrain and in particular batteries is more important in EVs [6, 7]. HVAC and transmission are other major components that need to be cooled down by the thermal management system in electrified powertrain.

Vehicle Thermal Management for EVs is challenging as it deals with the both the complexity of CAD and Multiphysics of electrified powertrain. The starting point for successfully creating a digital twin is to import 1000s of parts and then apply appropriate physics to the components to study the energy usage, passenger comfort and range all this can be evaluated in one integrated platform of Simcenter STAR-CCM+

4 Battery Cooling

There are lots of things to consider when designing an EV, in this case study the initial focus is on the battery cell and pack. The current dominant manufactural technology is Li-ion and there are no significant technological improvements that are expected to become commercially available in the very near future that can significantly improve the cell specific energy. The vehicle can be subjected to various drive cycles such as NEDC (New European Driving Cycle) [14]. It is comprised of 5 phases, 4 identical urban cycle followed by extra urban cycle which is at high speed, for a total duration of ~20 mins’ and total distance travelled is ~11km. This cycle doesn’t represent real life driving as it very soft accelerations, with a lot of constant speed and idle times. The NEDC drive cycle has been replaced by the WLTP (Worldwide harmonized Light vehicles Test Procedures) as a standard for evaluation of the emissions and range of vehicles which has been developed by the European, Japanese and Indian experts to overcome the shortcomings of NEDC. In this study the WLTC (Worldwide harmonized Light vehicles Test Cycles) Class 3 is used which is made of four speed zones: one representative of urban driving, one urban driving, one extra urban cycle, and a highway zone for a total duration of ~30 mins’ and total distance travelled is ~23km [14]. WLTC is a challenging drive cycle and designing of the battery cell and pack cooling system would be challenging as the thermal load will be higher with this cycle.

A vehicle battery design can be based on sizing dimensions, chemistry selection and thermal modeling [15]. Based on that set of targets different project teams can start doing modification and/or optimization of certain aspects of the car. The battery design process usually follows a similar V cycle but specific to Batteries as shown in Figure 1. The system level requirements can be translated to requirements for concept stage in the V cycle to create a digital twin of components and system. The battery thermal management can we divided into the following types;

1. Air Cooled (Natural or Forced)

2. Liquid Cooling
3. Phase Change Material
4. Oil Cooling.

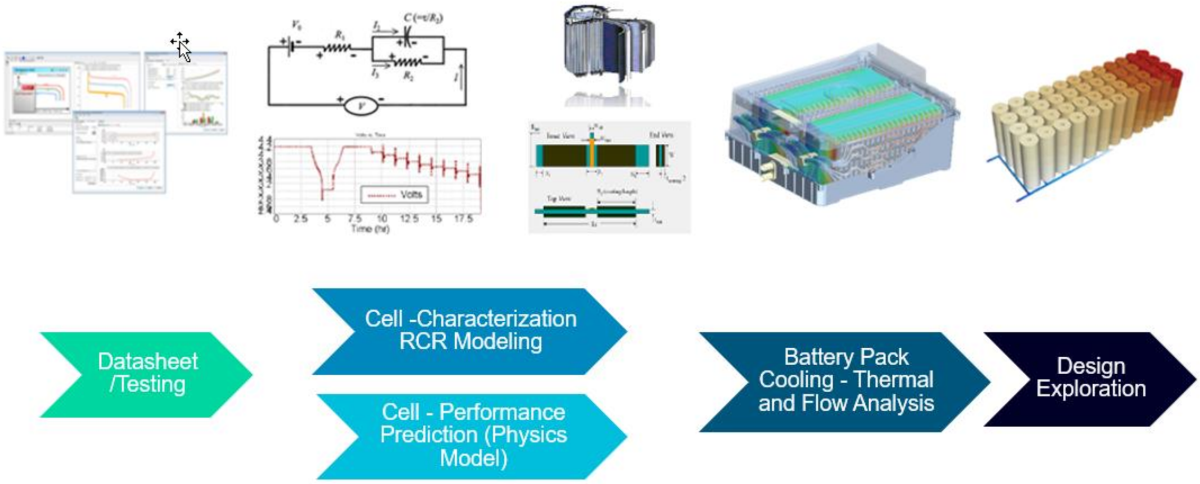

Fig. 2 Battery Cell to Pack Design Process

The starting point for pack level thermal management simulation would be to obtain the full characterized RCR modelled cell and to build the pack geometry as per the space constraints (See Figure 2). The battery cell can be designed as Physics or an Equivalent circuit (RCR) based design based on the available inputs and specification. This can be done in Simcenter Battery Design Studio which is 3D/1D electro-chemical-thermal solution for fully characterizing Li-ion cells by either using existing database or incorporating testing results. The cell is then virtually tested for varying duty cycles, c-rates, abuse and aging conditions. The cell can then be imported to perform pack level design in Simcenter STAR-CCM+ for performing pack level electro-thermal management. Using a pre-defined workflow in Simcenter STAR-CCM+ the cell pack can be easily configured as grid, staggered or custom where a high-fidelity battery pack was built. All the appropriate physics is applied to the battery stack, battery tabs, ancillaries and air to simulate the real-life scenario. It has an automated meshing workflow which is intelligent to identify the geometry details such as tabs, stack region and assigned boundaries conditions to apply appropriate mesh elements such as polyhedral, prism layers and thin mesh to the geometry. With the dedicated post processing the individual cell voltage, current, volumetric ohmic heat, electrode polarization heat and other relevant battery results are monitored and can be exported for system level analysis.

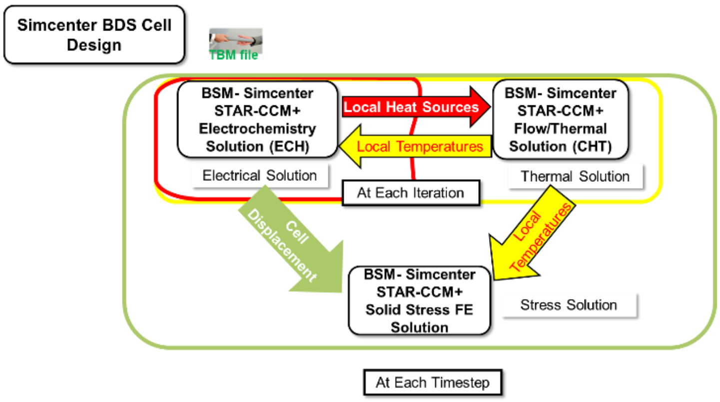

Fig. 3 Coupled solution for efficient battery modelling

It is important to accurately calculate the coupled behavior of electrical and thermal response of a battery over the course of the WLTC drive cycle. At each time step the energy solver needs to be updated with the new heat generation field which comes from the electro-chemical solver which get the updated temperature field to update the cell temperature dependent models, making it an interactive model to establish the cell response in its thermal environment. There should be a 2-way mapping to transfer the data from the electrical mesh to the thermal CFD mesh as shown in Figure 3. For a stack-based cell due to constant cycling the cell experiences expansion and contraction called as cell breathing and this needs to be accounted for longevity of the pack. The data from the electrical solver for cell displacement and the data from thermal solver to temperature rise is fed to the solid stress solver to calculate the Von-Mises stress acting on the cell and its ancillaries and this should be limited by introduction of foam and/or mechanical struts.

5 eMachine Cooling

The battery performance limits the driving range and the eMachine determines the driving performance such as speed and acceleration performance for an EV. Most dominate OEMs broadly use either permanent magnet synchronous motors (PMSM) and induction motors [8,9]. Both the above machines have similar configuration with variation in rotor only. The rotor in induction motors has bars and for PMSM it has permanent magnets to generate a rotating magnetic field. Permanent magnets are widely used in rotor for improving overall efficiency as the rotor losses would be lower (in comparison with induction motor), which could contribute to less heat generation in high-speed application. PMSM are also considered to obtain peak torque and high efficiency even at very low speed which serves as great application for electrical vehicles. The rotor primarily experiences rotor iron losses and magnet losses which generally increase with the size of the machine. The PMSM also provides greater flexibility to control machines over a wider speed range via controller and inverters.

Generally, an electric machine is a very complex thermal system, with different materials (copper, resin, steel, insulation tape, magnet, etc.) with varied temperature limitations [10, 11]. When a new electric machine is to be designed from scratch, the requirements usually include a set of performance specifications and a set of constraints or limitations such as the maximum physical size, the maximum temperature rise, and the supply voltage. In designing an electrical machine there are two models needed to be developed: One for the electromagnetics and another for thermal. For the electromagnetics care needs to be taken to avoid saturation of steel, eddy currents in the magnets and wires, harmonics, losses and continuously performing trade-off of active materials to achieve the required performance. Electromagnetic performance is not sufficient as the active materials are temperature dependent. There are two major aspects to the thermal problem in electrical machines - heat removal; and temperature distribution within the motor. The main reasons for limiting the temperature rise of the windings and frame of a motor are:

- To preserve the life of the insulation and bearings;
- To prevent excessive heating of the surroundings; and
- To prevent injury caused by touching hot surfaces.

In PMSM the temperature of the magnets needs to be kept under control, in order to avoid demagnetization which permanent effects the performance. The life of electrical insulation is inversely related to the temperature. The thermal management can be analyzed by either experimental test or by creating a virtual test bench either with a lumped model or 3D CFD model. In lumped model, the emachine is divided in sections are lumped into several thermal resistances and capacitances but this is less accurate and underpredicts for hotspots prediction and temperature gradient. The above drawbacks can be overcome by the 3D CFD model would provide detailed temperature gradient contour of each component within the emachine, but the analysis is computationally expensive.

To design and realistic machine we would need a true coupled electromagnetic and thermal solution as shown in Fig. 4. Modern computation methods are rapidly reaching the stage where a new prototype can be designed with such confidence that it will be "right first time", without the need for reiteration of design and test that would otherwise be necessary. Computer-aided design goes hand-in-hand with the modern design engineering environment essentially creating an eMachine Digital Twin. In this paper it is an extension of the work of the authors [12, 13] to add show the streamlined the process of the coupled behavior of an electric machine. The goal of electromagnetic analysis is to obtain losses from emachines, and the goal of thermal analysis is to obtain the temperature of components of emachines but the components such as winding and magnets are temperature dependent hence the above analysis need to be evaluated as a loosely coupled behavior of electromagnetic-thermal model for accurately losses and temperature prediction.

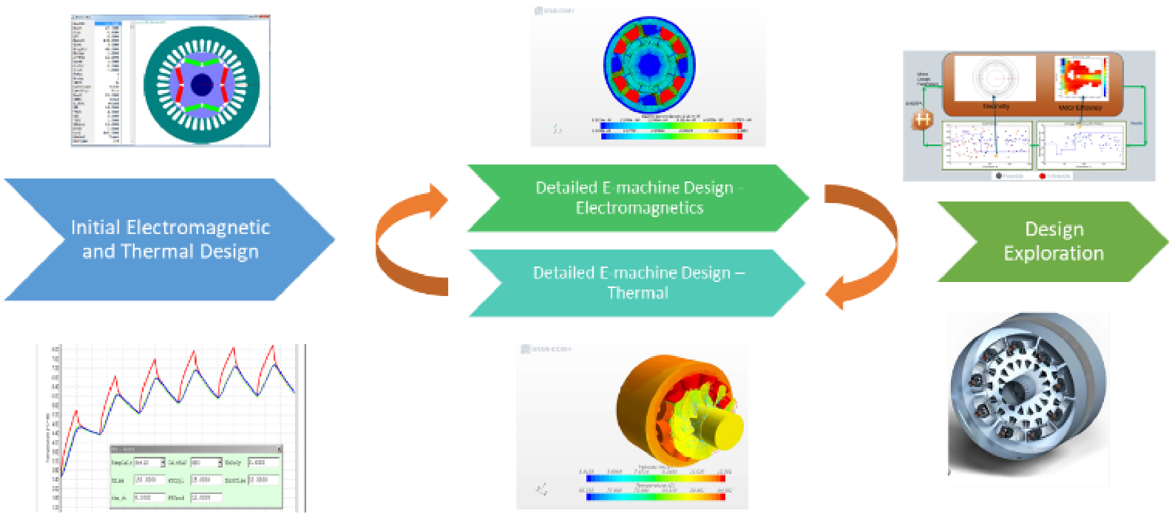

Fig. 4 eMachine Design Process

The initial emachine analysis can be performed in Simcenter SPEED which provides a quick electromagnetic thermal analysis for various emachine topologies. Once the design is selected then detailed coupled analysis is performed again in Simcenter STAR-CCM+. An automated method from the analytic solution is available to perform a detailed electromagnetic and thermal analysis called as GoTAR (Go do Thermal Analysis and Return) to capture the spatially distributed losses and temperature. In this process the user has options to select from various cooling methodologies and then the entire workflow is setup automatically from creating 3D-CAD, setting appropriate physics, boundary conditions such as flow rate, spatial distributed losses for individual regions and post processing results. The various cooling methodologies such as non-ventilated, internal of external fan cooling, liquid cooling with radial, axial or spiral jackets. GoTAR automatically sets up the co-simulation process through JAVA macros which essentially means for every time-step the initial electromagnetic design gives the essential losses which are mapped on the thermal model to predict the rise in temperature and those temperatures are mapped on the electromagnetic mesh to get the new winding and magnet losses which are temperature dependent. This toggling back and forth between electromagnetic and thermal solution process is continued until the temperature converges which is usually achieved in about five cycles. Since the real time scales for one electrical cycle takes milliseconds where are reaching steady temperatures takes minutes are so different and hence a loose coupled solution is proposed with the workflow as shown in Fig. 5.

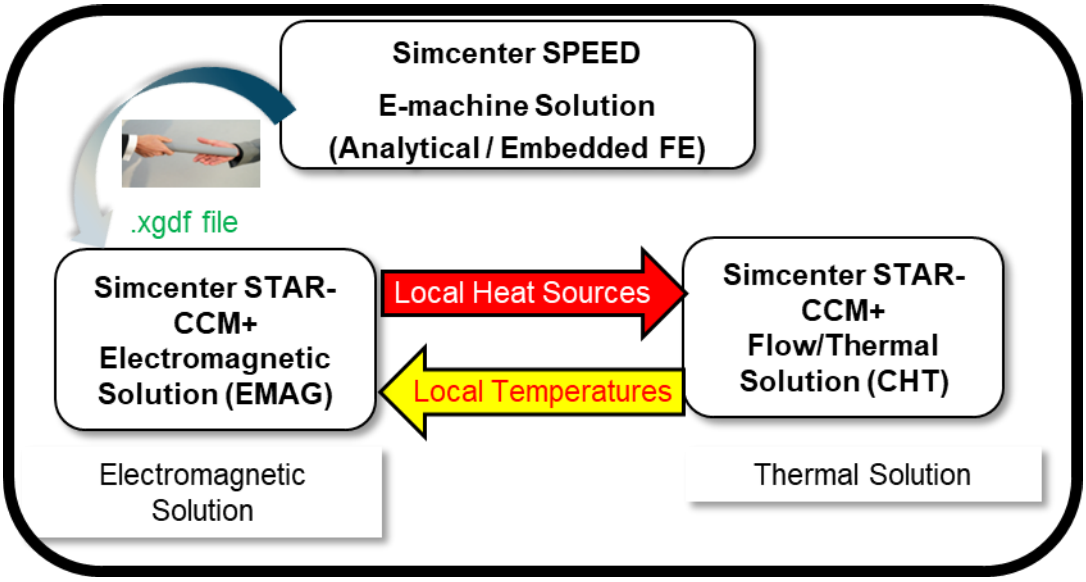

Fig. 5 Loosely coupled automated process for electromagnetic-thermal modelling

There are numerous benefits from this approach where the user doesn't need to spend time on the setup and onus is provided to the user to analyze the solution but there are two drawbacks with this approach - JAVA macros need to be maintained as the code undergoes numerous enhancements and there is fear of deprecated macros. The other is the manual or scriptable macro update of the local temperature and local heat sources. In this paper we proposed along with the GoTAR, usage of Simulation Operations. Simulation operations allow you to automate the solution processes in Simcenter STAR-CCM+ without using Java macros. Condition and loop operations provide the basic logic control common to many programming languages. The question of how to switch between solvers in a fluid continuum and a solid continuum alternately until the overall solution converges is answered with Simulation Operations which interact with other control features in the Simcenter STAR-CCM+ interface. For example, the Solve Physics (Continua) operation activates solvers that belong to models chosen for a particular physics continuum and iterates until solver-specific convergence criteria are met. Simcenter STAR-CCM+ not only offers an integrated platform to handle flow and thermal as well as capabilities but also to simulate magnetic fields in the machine in 2D or 3D for electromagnetics problems.

With this addition of Simulation Operations, the initial setup phase provided by the GoTAR process is carried further into a then self-contained and therefore easily repeatable simulation to achieve converge on the final losses and temperature of the emachine.

6 Case Study on Pure EV

In designing a commercial EV SUV as shown in the Fig. 6 car for this paper, the first step is to get the specification. In this paper we will refer to this car as Pandora SUV. The specifications are full EV, target range ≥ 320 km; eMachine with rated 275 hp

@7000 rpm, Battery with 80kWh, 250 Wh/km. The battery design process usually follows a V-cycle as shown in Figure 2. In this paper we would focus on the concept, and detailed ePowertrain design shown in Fig 7 based on the above requirement.

Fig. 6 Pandora SUV CAD Model in Simcenter STAR-CCM+

Vehicle Thermal management results helps to analyze the high risk of battery pack at harsh operating condition and best location of it that suffice the proper cooling of Battery as well as Electric Motor. Simulation insights also give the optimal energy consumption for the HVAC thus the safety and comfort of the passengers. Below images strike the safety and risk management of Battery pack mounting, location, cooling system, accessibility and passenger safety.

Fig. 7 Pandora SUV CAD Model with electrified powertrain

7 Results

7.1 Results from eVTM

Assessment from Thermal Management for Electric Vehicles caters the thermal behavior of the batteries, power electronics and motors, considering the material and engineering solutions used throughout each component. Whilst thermal management is a key consideration for any electric vehicle, there is no consensus on the best design. This stems from the fact there is also no consensus on the best way to construct an electric vehicle, from the battery cell, module and pack construction to the type of electric motor used. Hence a complete Vehicle Thermal Management is the only way of solution that brings the value of virtual validation against repetitive physical prototypes and testing. Figures 8 shows Heat Rejection majorly from Battery Pack and E-Motor and Heat Transfer through Radiator where the maximum temperature of battery is 14 °C and maximum temperature of eMachine is 106 °C assuming a constant heat load for both eMachine and batteries. Performing a coupled simulation through the integrated workflow in STAR-CCM+ i.e. First performing analysis on the Batteries and then the eMachines to get the heat load and temperature mapped for the full vehicle thermal management. The results where different and more accurate as the maximum temperature of the battery is 16 °C and maximum temperature of the eMachine is 112 °C.

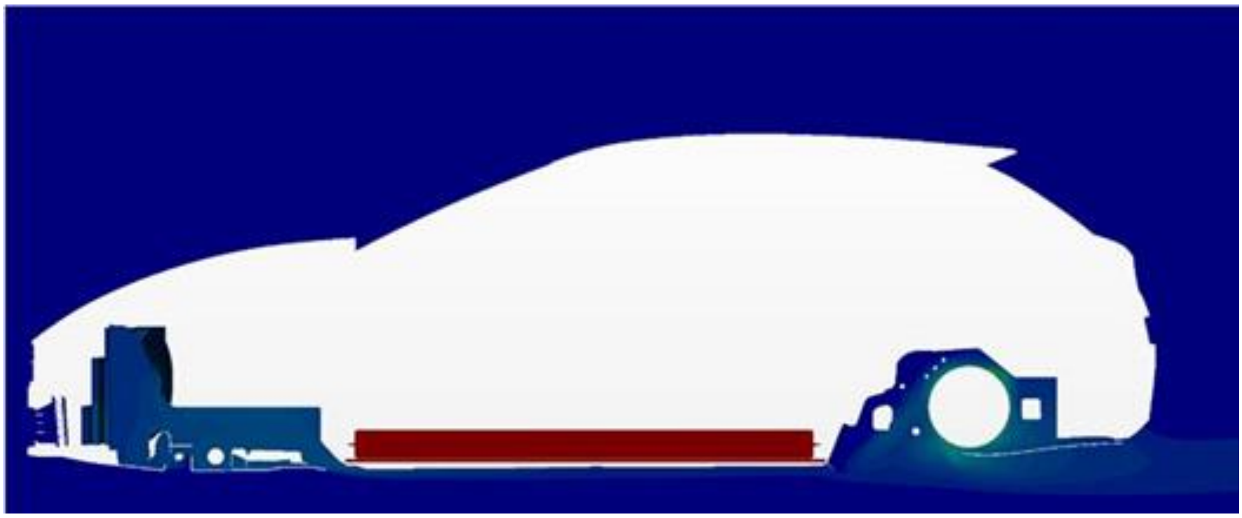

Fig. 8 Pandora SUV Temperature distribution across the electrified powertrain

Figure 9 shows External Aerodynamics as well as the flow field around the heat sources Battery pack, e-motor, inverter—etc. In a single simulation one can study the aerodynamic shape of the car, front end air flow from the grill and other openings, mounting location of Condenser, Radiator, fan and other e-powertrain components and their reliability & performance. Besides the aerodynamics effect on the design and drive range there is another key decisive factor is drive range. Air-conditioning and heating of the interior are considerable power consumers and significantly influence the EVs range, especially at extremely low or high ambient temperatures. A range reduction caused by the air-conditioning system at extreme ambient condition can be analyzed. In this simulation, the power consumption of a full electric car was measured while driving the adapted Worldwide Harmonized Light Vehicles Test Procedure (WLTP) driving cycle.

The VTM analysis provided the holistic view of the vehicle's temperature, the next section provides greater insights into component level design of battery and eMachines.

Fig. 9 Pandora SUV Temperature distribution across the electrified powertrain

7.2 Results from Battery Cooling - Battery Cell and Pack Design

The system level requirements drive the concept of battery sizing and cell choice. A stack cell configuration is selected which can be designed in Simcenter Battery Design Studio (BDS) [6] which provides a user-friendly selection of templated cell configurations, database of materials and different electrodes designs. From the existing databases [3] of electrodes LiFePO4 – SLP Graphite a 50Ah/3.2V cell is designed with electrolyte LiPF6 salt with solvents which is subjected to 0.3C, 1C, 2C discharges curves. Different approaches are used for modeling of lithium-ion batteries and their aging. The most realistic cell models are physics ones which simulate mostly single aging effects such SEI growth, lithium plating, electrolyte decomposition, corrosion of electrodes etc. However, these models are very slow and complex to parameterize. Therefore, they are not suitable for aging prediction on a long-time scale hence an empirical aging model would be suitable. For an aging prediction a lot of different aging factors must be accounted e.g. temperature, storage voltage and time for calendar aging and in addition cycle depth, SoC range, current rate and charge throughput for cycle aging considering both calendar and cyclic aging. An enhanced of the implementation from the [2] has been included in Simcenter Battery Design Studio (BDS) to account for capacity loss and resistance rise through a holistic aging model based on electrical-thermal model. The resistance and capacitance parameters are scaled by accounting for variation is cell’s activation energy, voltage dependency, depth of discharge and temperature. A physics-based cell design aging results are used as physical test results for various measurements and are fit to the Siemens Aging Model. The cell fit results are favorable as shown in Fig 10 the capacity factor RMSE is less than 2% which was the objective of the fit. The Fig. 11 shows the various baseline and regressed fit aging parameters variation. This has been achieved by regressing the RCR Aging model parameters from the small dataset of the accelerated lifetime tests (for one year) to capture the multi-attributes of aging and predict the aging for the full life term of the application. In summary this data driven cell degradation implementation can be applied to any drive cycle where the resulting fitting functions include the dependency of capacity and resistance with respect to time, temperature seasons, charge throughput and the other varied parameters. The cell is fully characterized, and next step is to perform a pack analysis.

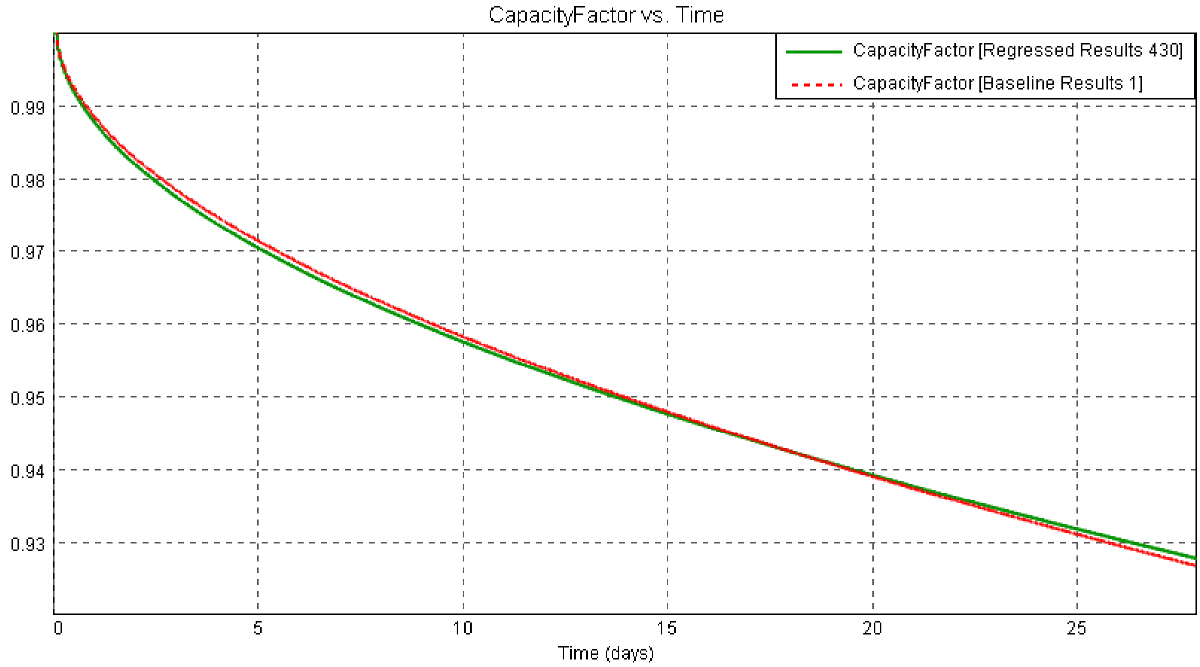

Fig. 10 The capacity factor over cycle depth for WLTC drive cycle at 35 °C.

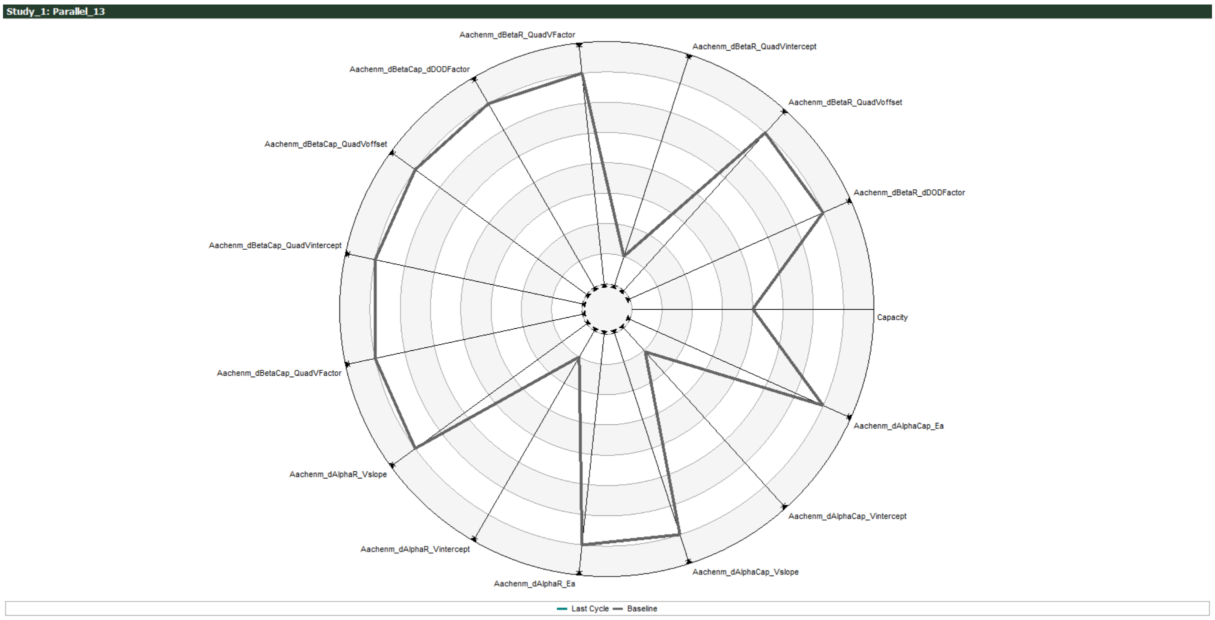

Fig. 11 Spider map of aging parameters of the baseline

The pack is made of 38 modules with four cells in series and 3 in parallel and arranged as shown in the Fig 12. The maximum temperature rise for the Battery pack is approximately 16 °C the battery pack is analyzed with air cooled thermal management as the temperature rise acceptable for a WLTC drive cycle but for more aggressive drive cycle liquid (water ethyl-glycol) cooling would be is the starting point for thermal management. Based on rise in temperature of cells appropriate cooling methodology is selection.

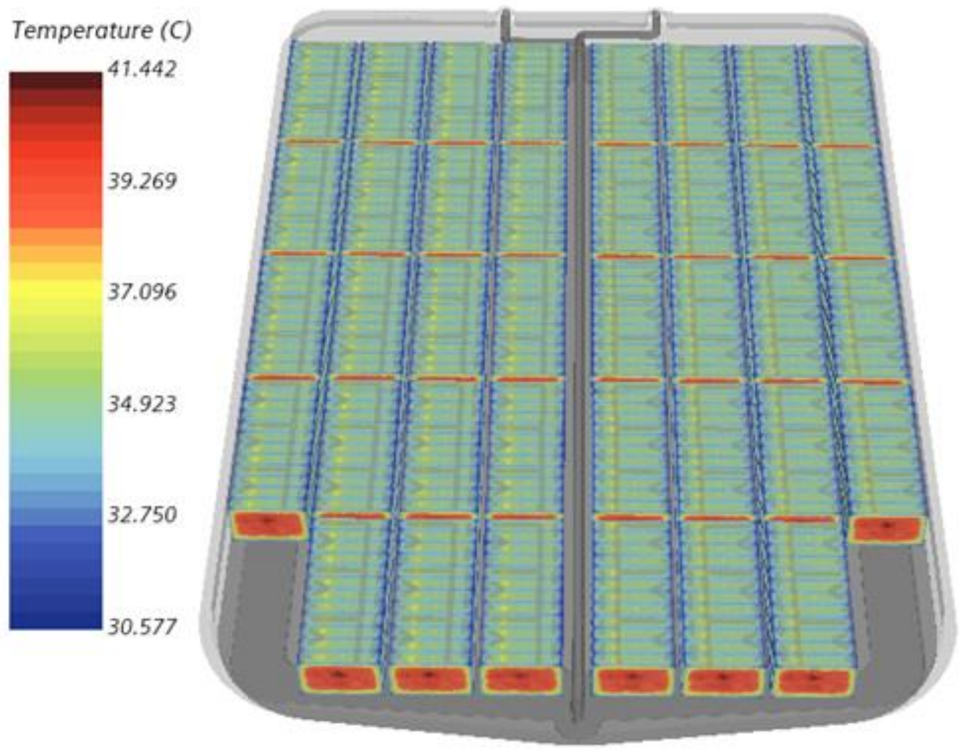

Fig. 12 Battery Pack Temperature contour with the ancillaries

For simulating the performance of the pack for a WLTC class 3 drive cycle and to make it computationally effective the simulation was run on the last extra urban cycle only and not on entire drive cycle as that is most aggressive and would contribute to highest temperature rise for the pack

7.3 Results from eMachine Cooling - Initial Machine Design

To simplify the presentation of this work we begin by considering a PMSM machine, a Nissan Leaf open source model was selected as per the below specifications.

Tab. 1 Electrical Machine Specifications

Slots	48
Poles	8
Maximum Torque /	280 Nm / 80kW
Maximum Speed	11400 rpm
Operating Speed	7000 rpm
Voltage range	250-400 V
Max Peak Phase	265 A

The motor data was obtained from published materials from either the Oak Ridge National Laboratories (ORNL). The geometric model information furnished by ORNL is added in robust machine sizing software Simcenter SPEED template [2]. The material and winding information was also provided by the ORNL. The experimental results for evaluating the performance of the machine against simulation were obtained from the

ORNL and are presented. A two-layer magnet arrangement is designed to obtain very sinusoidal induced voltage which is due to high difference in d-axis inductance and q-axis inductance.

The complex geometry is input using available templates in Simcenter SPEED. A high pole number is selected to reduce the yolk weight. In the figure the flux barriers are in hollow region around the steel which is represented in yellow; it improves the flux concentration, path and to minimize permanent magnet volume. Iron mass is reduced, and special attention is paid to mechanical strength. The open circuit EMF, current waveform, cogging torque and operating torque for the speed range has been validated.

The Simcenter SPEED tool provides a complete interface for initial characterization of an electrical machine such as winding, thermal and control strategies to address the electromagnetic design. To design a higher power density machine, it is important to account for magnetic saturation of a machine and SPEED provides a unique embedded FEA solver which automatically adjusts the analytic solution to match the FEA solution. In this paper a single load point computation is performed to determine the saturated inductance values in the d-axis and q-axis. This provides an ability to accurately predict the electromagnetic solution. The detailed 2D electromagnetic results are shown here where the max flux density in the teeth is 2.1T which is approaching saturation. And on the right, you see the core losses and the magnet loss of the machine for the worst case operating point of 80kW , 267A peak which results in 598.80W of loss due to stator core loss, 13.20W as rotor core loss and 3.20W as magnet loss. But Magnet Losses are 3D in nature, and it needs to include the effect of segmentation which is done to reduce the eddy current effects and hence the losses. For the 3D electromagnetic run to capture magnet losses after segmentation to reduce the losses without impacting the torque. By segmenting these magnets, the losses were reduced by 40%.

The idea for designing a machine is to have a balance of electric loading and magnetic loading to optimally using the active material. Here we see the 3D model which has a distributed winding with the unique rotor lamination design to achieve high flux linkages with the stator winding. The cooling of the machine is achieved by a unique water jacket design which is composed of 3 jacket rings which are connected via small bridges. The coolant is 50% - 50% water-ethyl glycol which we hope would be able to remove the dissipated heat from the machine we observed from the EMAG results. In Fig. 13 both EMAG and Thermal results together. In order to assess the performance of that cooling system, the machine is run at the most critical load point, which is at 80kW and 7000 RPM. The maximum temperature elevation that the winding temperature does not exceed the 155 °C which is the maximum temperature allowable for the winding as it has a class F insulation. The maximum temperature of winding is 112 °C and the average temperature of the winding is 79 °C.

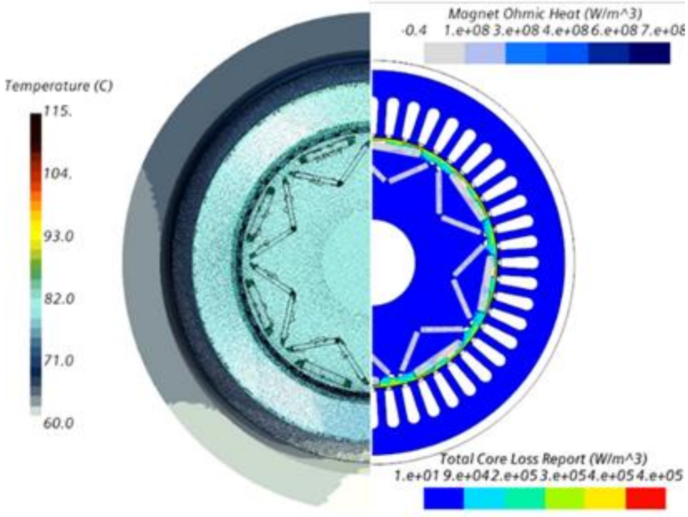

Fig. 13 eMachine’s Thermal Temperatures and EMAG Losses

The pressure and the fluid vector field in the channels as shown in the Fig 14 one can notice some inefficiencies whereby a lower pressure drop, and flow rate would make the cooling system being more energy efficient and this is critical when this is used on a full electric vehicle.

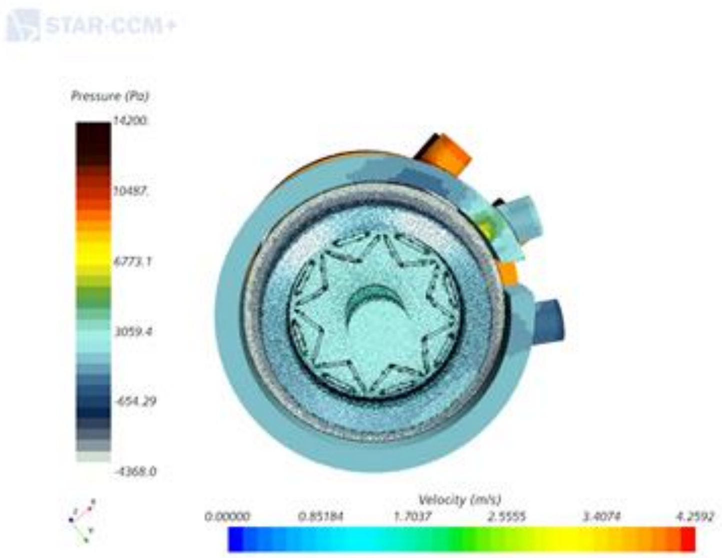

Fig. 14 eMachine’s Liquid Jacket Pressure drop and Flow rate

8 Conclusions

In this paper the role and importance of having a true Multiphysics platform for handling the eVTM was analyzed and then a case study was showcased with results from an integrated workflow to component level results into the full vehicle thermal analysis considering various multi- attribute and physics for greater insights at a vehicle level. And with that one could design a true digital twin of an Electric Vehicle considering all the Multiphysics aspects and looking at in detail ePowertrain components and be-low the acceptable temperature limits for safe operation.

In Pandora SUV, the entire ePowertrain performance has a key role in providing a long driving range, fast acceleration, long life, and even low overall costs. Although the ePowertrain technology is challenging the status quo of ICEVs at many fronts i.e. its performance, fuel economy, and life but it is also highly dependent on operating temperatures. Additional heat loads from power electronics, HVAC, radiators should be considered for VTM for completing the digital twin of the vehicle. In particular the temperature gradients on the ePowertrain have significant impact on the life of the battery and likelihood of propagation of thermal runaway. Hence close attention is needed to be paid to VTM to maintain the battery and eMachine with the operating temperature ranges.

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