Abstract

This paper covers various design aspects of electric vehicle development with main focus on powertrain system. In the first section of the paper, conceptual design issues including the types of electrical machines for electric vehicles are studied and a schematic is proposed as a guideline for development steps.

As part of a national R&D concept, design activities in an electric vehicle project is presented, which covers development of an interior permanent magnet synchronous machine drive, vehicle control unit and experimental setup. On-going status in the project, simulation and test results are given.

I. Conceptual Design and Development Methodology of an Electric Vehicle

Introduction

The market demand on electric vehicles is expected to increase in near future. The main obstacles to electric vehicles are component cost especially high voltage batteries, limited range, and lack of infrastructures of charging stations as well.

Main topic of this paper is to present the on-going design activities in an electric vehicle project. The project aims to develop a vehicle control unit and a drive system for an interior permanent magnet synchronous machine which will be integrated into a prototype electric vehicle for public transportation. Specific design issues are intended to be discussed in a future paper.

A. Design Process

R&D in automotive field is a complex process, where OEM, component suppliers and engineering companies cooperate together. Electric vehicle technology has differences than conventional vehicles in terms of traction motor, energy source, engineering problems, subcomponents and component suppliers. Therefore, project management of an electric vehicle development has specific issues.

To this end, the schematics in figure 1 is proposed as a guideline to define the main development steps of an electric vehicle. As can be seen in the schematics, definition of the vehicle performance criteria, drive cycles, geography and climate, specifications and component suppliers should be
analysed simultaneously. At the end of this process, four main parameters can be listed as the outputs:

- Cost
- Efficiency
- Weight
- Range

Decision on whether the vehicle should be a new design electric vehicle or an electric vehicle conversion can be based on the assessment of these outputs along with the market segment and annual production volume.

*EPAS Steering System: Electric Power Assisted Steering System*

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It can be concluded that electric vehicle conversion is quick and cost effective solution, whereas the vehicle performance parameters may not be optimal. Design of a new electric vehicle provides more flexibility to optimize vehicle performance parameters and subsystems like weight, range, driveability, NVH (noise-vibration-harshness), regenerative brake, dedicated control algorithm in vehicle control unit etc.

Weight reduction has direct impact on the range of an electric vehicle. In [1], impact of the weight on power demand is analysed experimentally. Referring to this analysis, every 200 kg additional weight has 2.72 kW additional power demand at %15 grade at 30 km/h constant speed. It should be underlined that this result is given for the vehicle parameters in that experiment. Compared to flat road, impact of weight is increasing at grade because of the additional resistance of gradient $m \cdot g \cdot \sin(\theta)$ in the longitudinal vehicle dynamics model. In [2], comparison of the weight of the subcomponents of a conventional vehicle and an electric vehicle is given.

B. Selection of the Electrical Machine Type

One of the important steps in the design process is the selection of the type of the electrical machine. A brief evaluation is given below.

Considering the commercialized electric vehicles and automotive suppliers, induction machine (IM) and interior permanent magnet synchronous machine (IPMS machine) are the most commonly used electrical machines in electric vehicles.

Main advantages of IPMS machine over IM are the higher efficiency at low speed, high torque/volume ratio and lower weight. In [3] and [4], a comparison of IPMS machine and IM has been made over a city and highway drive cycle. Although these results may change depending on the machine design and drive cycle profile, it clearly indicates that IPMS machine provides higher efficiency and hence longer range at city cycles. In [4], loss analysis is also given for IM and IPMS machine. Based on this analysis, it can be concluded that energy consumption for cooling of IM is higher than IPMS machine which is another design issue for energy management and range estimation as well.

An analogy for IM and IPMS machine can be made such that IM would be the counterpart of gasoline engine whereas the IPMS would be the counterpart of Diesel engine [1]. In case of IM, trade-off is lower efficiency in city cycle vs. lower cost for the customer. In case of IPMS machine, trade-off is higher efficiency vs. higher cost for the customer.

In the last few years, because of the supply problems of rare-earth elements, cost of IPMS machine is increasing. Therefore, electrical machines like permanent magnet-assisted synchronous reluctance machine (PMA-SRM), externally excited synchronous machine, and switched reluctance machine are considered as alternative solutions for electric vehicles.
Externally excited synchronous machines developed by Continental have been applied to electric vehicle applications of Renault [5]. Design details are given in [6].

PMA-SRM with ferrite type magnets has both magnet torque and reluctance torque component. It is similar to IPMS machine and a cost-effective alternative as well [7-8].

Critical parameters and requirements for the selection of an electrical machine can be listed as follows [1]:

- Insulation class H
- Water cooling is required both for electrical machine and inverter. Because the drive cycles, including the increase in ambient temperature, imposes thermal stress on EM and inverter as well.
- Short term overload capability. The range of peak torque to maximum continuous torque should be 1.5 to 2.
- Maximum speed to nominal speed ratio, e.g. wide field weakening range. Ratio of 3:1 or 4:1 is common in practice.
- Design voltage considering the battery minimum and maximum voltage range
- Maximum continuous torque and peak torque for grade and acceleration requirement
- Maximum speed considering the gearbox ratio
- Efficiency map. This is related to power demand for cooling of electrical machine, drive system and the battery for estimated drive cycles, heating of the battery for minus temperatures as well.
- Protection class IP6K7
- Weight
- Geometrical integration into vehicle
- Cost and supplier

As a conclusion, design of an electric vehicle has many aspects which should be analysed simultaneously.

II. Development of Interior Permanent Magnet Synchronous Machine Drive System and Vehicle Control Unit

As part of an electric vehicle project, drive system for an IPMS machine and vehicle control unit (VCU) are developed in the project. The vehicle is aimed to run in a city traffic. Therefore, IPMS machine is chosen due to its higher efficiency at low speeds and high torque /volume ratio as well.

The project has several phases. A generic motor drive for IPMS machine which is fed by three phase 400 V supply is developed at first phase. At second phase, another version which will be compatible for specifications and requirements for the prototype electric vehicle will be developed.

Control models of VCU has been developed in Matlab-Simulink and code generation has been implemented on a fast prototyping VCU hardware. CAN
interface of VCU has been implemented and tested on a 2 kW industrial motor drive.

At the next step, hardware of VCU is to be designed as well. Final products of the project will be as follows:

1. Drive system of IPMS Machine (design of power electronics and control board and software including the vector control algorithm, CAN I/O and user interface for calibration.
2. VCU hardware and software including the control algorithm, CAN I/O and user interface for calibration.

A. Vector Control of IPMS Machine Drive System

Motor drives for electric vehicles have different specifications than industrial drives in terms of input voltage, switching frequency, water cooling etc.. A comparison between industrial and electric vehicle motor drives can be found in [1].

The main specifications of the high power motor drive in the project is as follows:

- 75 kW nominal, 150 kW peak power
- Input voltage range of the inverter is between 250-600 V DC
- Switching frequency is 10 kHz
- Space Vector Modulation
- Max. speed up to 10,000 rpm
- CAN interface for communication with VCU
- Water cooling

Mathematical model of an IPM S Machine in d-q reference frame is as follows:

\[
U_{sd} = R_s \cdot i_{sd} + L_{sd} \cdot \frac{di_{sd}}{dt} - \omega_r \cdot L_{sq} \cdot i_{sq} \tag{1}
\]

\[
U_{sq} = R_s \cdot i_{sq} + L_{sq} \cdot \frac{di_{sq}}{dt} + \omega_r \cdot (L_{sd} \cdot i_{sd} + \psi_{pm}) \tag{2}
\]

\[
T_e = \frac{3}{2} \cdot p \cdot \left[ \psi_{pm} \cdot i_{sq} + (L_{sd} - L_{sq}) \cdot i_{sd} \cdot i_{sq} \right] \tag{3}
\]

In order to utilize the reluctance torque component, Isd current should be applied on the d-axis. Maximum Torque Per Ampere (MTPA) strategy provides minimum current for a given torque reference and therefore it is implemented as part of the vector control. Based on MTPA strategy, d-axis current reference is given as follows [9]:

\[
\hat{i}_{sd, ref} = \frac{\psi_{pm} - \sqrt{\psi_{pm}^2 + 4 \cdot (L_{sq} - L_{sd})^2 \cdot i_s^2}}{4 \cdot (L_{sq} - L_{sd})} \tag{4}
\]
Voltage and current limits of an IPMS machine fed by an inverter are given as [9]:

\[
i_s = \sqrt{i_{sd}^2 + i_{sq}^2} \leq i_{s\text{max}}
\]

\[
U_s = \sqrt{U_{sd}^2 + U_{sq}^2} \leq U_{s\text{max}}
\]

As the modulation method, Space Vector Modulation is implemented and therefore voltage limit is given as [9]:

\[
U_{s\text{max}} = \frac{u_{dc}}{\sqrt{3}}
\]

Where,

- \(u_{sd}, U_{sq}\): d and q-axis voltages [V]
- \(i_{sd, \text{ref}}, i_{sq, \text{ref}}\): d and q-axis current controller references [A]
- \(i_{sd, \text{act}}, i_{sq, \text{act}}\): d and q-axis actual currents [A]
- \(i_s\): Phase current
- \(\psi_{\text{pm}}\): Rotor permanent magnet flux [Wb]
- \(T_e\): Motor torque [Nm]
- \(p\): Pole pair number
- \(L_{sd}, L_{sq}\): Stator d and q-axis inductances [H]
- \(R_s\): Stator resistance [Ohm]
- \(I_{s\text{max}}\): Motor/inverter current limit [A]
- \(U_{s\text{max}}\): Inverter voltage limit [V]
- \(U_{dc}\): DC-link voltage actual value [V]
- \(\omega_r\): Rotor electrical speed (rad/s)

\(L_{sd}\) and \(L_{sq}\) inductances are functions of the current for an IPMS machine. The variation is more critical especially at field weakening range. \(L_{sd}\) and \(L_{sq}\) are assumed to be constant and motor nameplate data is used for the operating point at experimental results in this study.
**Implementation and Experimental Setup**

Inverter section consists of Fairchild IGBT modules with 1200 V and 20 A ratings. Switching frequency of Space Vector Modulation is set to 10 kHz. Vector control algorithm is implemented on Texas DSP F28335. Experimental tests of motor drive is done on a 2.2 kW IPMS machine from Yaskawa and nameplate data is as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Rated power</td>
<td>2.2</td>
<td>kW</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1750</td>
<td>rpm</td>
</tr>
<tr>
<td>Rated torque</td>
<td>12</td>
<td>Nm</td>
</tr>
<tr>
<td>Rated voltage (rms)</td>
<td>373</td>
<td>V</td>
</tr>
<tr>
<td>Rated current</td>
<td>4.1</td>
<td>A</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>3.29</td>
<td>Ohm</td>
</tr>
<tr>
<td>d-axis inductance</td>
<td>40.39</td>
<td>mH</td>
</tr>
<tr>
<td>q-axis inductance</td>
<td>57.06</td>
<td>mH</td>
</tr>
<tr>
<td>Rotor inertia</td>
<td>10.07x10^{-3}</td>
<td>kgm^2</td>
</tr>
</tbody>
</table>

The Simulink models have been converted into C by using the Embedded Coder, Simulink Coder and Matlab Coder Toolboxes of Matlab. These toolboxes work cooperatively to generate target specific C and C++ code that satisfies some globally admitted coding standards. Code generation with these toolboxes speeds up the development process and saves time. Model design file is composed from Simulink blocks, Matlab Code blocks and C code blocks that includes software algorithm, target specific blocks (PWM, Interrupt etc.)

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and memory allocations that depend on the storage components. Some other configuration parameter settings like cycle period, debugging and building operations settings are necessary to generate the code compatible with the target processor. When the model build operation is completed correctly, an IDE (Integrated Development Environment) program like CCS (Code Composer Studio) is necessary to load the generated .out file into the target processor.

![Fig. 3 Implementation of Vector Control Algorithm in Matlab Embedded Coder Toolbox](image)

**Fig. 3** Implementation of Vector Control Algorithm in Matlab Embedded Coder Toolbox

![Fig. 4 a) Motor drive prototype b) IPMS machine and test bench](image)

**Fig. 4** a) Motor drive prototype b) IPMS machine and test bench

**Experimental results**

Prototype motor drive has been tested on the test bench in closed loop speed control mode. As seen in fig.5, 10 Nm torque is applied stepwise at 500 rpm speed reference.

Actual values of current and speed controllers follow the references with minimum overshoot.
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A. Development of Vehicle Control Unit

Design of VCU has vehicle specific and also generic features. In this project, a general purpose VCU is designed which can be adapted for a new design electric vehicle and also electric vehicle conversion applications. At first phase, control system software and CAN interface is designed and implemented on a fast prototyping VCU hardware. At second phase, VCU hardware will be designed as well.
As in Hybrid Electric Vehicle (HEV), VCU of an electric vehicle has modules like torque control, energy management, CAN interface, finite state machine etc. [10].

The VCU topology in the project is as follows:

![VCU topology of an electric vehicle](image)

**Fig.6 VCU topology of an electric vehicle**

VCU is designed in a simulation platform consisting of the following main modules:
- Human driver model
- VCU
- Inverter and electrical machine model
- Gearbox
- Vehicle model
- Mechanical brake model
- Battery model

For the sake of simplicity, all signals are not shown in fig.7.

![VCU development platform in Simulink](image)

**Fig.7 VCU development platform in Simulink**

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In fig. 8, as a conceptual study, simulation of electric vehicle controlled by VCU is shown for NEDC city cycle, where vehicle is shutdown due to an emergency case or a critical fault at t=736 s. VCU sets the torque reference to zero and vehicle enters coast down state at t=736 s. The following data is used in the simulations:

Total mass of the vehicle is 6000 kg, continuous maximum and peak torque of electrical machine is 250 Nm and 400 Nm respectively, battery energy is 60 kWh. Longitudinal vehicle dynamics model in simulation is a single-wheel model.

In fig.8, regenerative and mechanical brake torques are combined at fixed ratios, e.g. %50 of total brake force for regenerative brake and mechanical brake are allocated. Regenerative and mechanical brakes are applied simultaneously.

Pedal signals are sent from human driver model to VCU. VCU calculates the torque reference including the regenerative torque reference and send it to inverter and electrical machine model. Torque reference of electrical machine has traction mode and regenerative mode components. Torque reference in regenerative mode is limited in VCU and motor drive as well. Torque control module of VCU calculates the limits of regenerative torque depending on the battery SOC and braking force distribution of the vehicle as well.

`a) Torque and speed curves at NEDC cycle for the test case`
b) Battery State of Charge (SOC)

c) Acceleration and brake pedal position signals

Fig.8 Simulation of electric vehicle controlled by VCU. Emergency shutdown is applied at t=736 s.

Experimental Setup

Using the code generation tool of the VCU fast prototyping system, Matlab-Simulink and Stateflow models have been converted into C.

VCU models have been tested on a 2.2 kW motor test bench. Main purpose of this configuration is to establish the CAN communication between VCU and electric powertrain drive and send torque reference via VCU torque control.
model, monitor the status of the motor drive via CAN bus, and apply other test conditions to test VCU software.

Most industrial inverters in the market have CANopen® protocol. In the first phase, the goal was to examine CANopen® protocol and its functionality. After analyzing the Draft Standard DS301 [11], initial CANopen® communication software was implemented.

**Fig.9 VCU development and test platform**

In the experiments, Control Techniques SP1406 motor drive was chosen. Control Techniques motor drive performs communication on DS301 (Application Layer and Communication Profile) and DS402 (Device profile for Drives and Motion Control) device profile which is specified for motor drive control [12]. The CANopen software implemented in this phase supports SDO-only (Service Data Object) communication. Thus, the motor drive is able to run in motion control modes. In order to run in different motion control modes, prewritten line by line command sets are needed. Therefore, it is not practical for the test system. In case of fault or to work in different mode, software needs power-up reset and user has to re-select the configuration command set.

**Fig.10 Debugging of VCU software via CAN Analyzer**
In the second phase, a CANopen finite-state machine was added to obtain a smarter control. Therefore, after switching the ignition key to ON position, VCU is able to control the motor drive by itself. The state-machine was programmed to have the software compatible with CANopen based motor drives. To accomplish this, CAN state machine of VCU was programmed to work as a master CANopen device. Thus, VCU checks the state of inverter, configures if needed, and controls it. Unlike the first version, the state-machine uses SDOs and PDOs as communication objects. In CANopen protocol, PDO (Process Data Object) message objects are used for real-time data transmission [11]. By the help of PDOs, the second version yielded efficient and fast control. As a consequent, the work in communication part yields expected results.

CONCLUSION

In this paper, development of an electric vehicle powertrain is studied both from conceptual and practical aspects. 2.2 kW vector controlled IPMS motor drive prototype is presented with experimental results. Implementation of field weakening is on-going. 2.2 kW IPMS motor drive is a low power prototype of electric vehicle motor drive. Considering this target, both power electronic design and vector control algorithm is implemented and improvements are on-going.

Simulink models of VCU has been developed in a simulation platform which is developed especially for electric vehicles. Test with an industrial motor drive has been realized in order to verify the CAN communication of Simulink models of VCU with external peripheral units. Next step in the project is to design a high power motor drive and a test bench for electric vehicle powertrain, and also develop a VCU electronic board as well.

At final stage of the project, these components will be applied to the prototype electric vehicle.

REFERENCES


Acknowledgement
On behalf of OTAM A.S., authors would like to express their thanks to Yaskawa Germany for their kind support on supplying the interior permanent magnet synchronous motor.


[12]CiA® 402 CANopen Device profile for Drives and Motion Control http://www.can-cia.org