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OPTIMAL TORQUE ACTUATIONS OF AN ELECTRIC DRIVETRAIN USING CONVEX OPTIMIZED POWER FLOWS

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Abstract. This paper presents a methodology for the determination of the optimal torque set points actuated to a pair of induction machines which is part of a battery-convertor-induction machine subsystem that on his turn is connected to a variable input load. The torque values of this large scale mechatronic system are determined by convex optimization of a general loss function incorporating switching losses, conduction losses, resistor losses, and mechanical friction of the considered drivetrain. Behavioral physics-based models are used to acquire the power flows and corresponding losses are calculated. The dynamic optimization formulation is casted to a convex minimization problem for the computationally efficient assessment of the torque set points. Results show that the proposed method is able to determine in a computationally efficient way the torque set points in this drivetrain for variable input loads.

Keywords: Control systems, mechatronics, dynamic systems, convex optimization, electromechanical drivetrains.

INTRODUCTION

Combustion engine-based vehicles have been able to experience a whole range of ongoing innovations throughout the last decades, thanks to their popularity in use and the lack of an equivalent alternative. Hybrid and all-electric vehicle technology only had the chance to evolve during recent years, because non sufficient knowledge was present in earlier times and customers did not feel the urge to buy more ecological cars. Therefore a large margin for improvements does still exist and similarly to the fuel efficiency in diesel and gasoline propelled cars, the conversion of electrical energy from energy source towards motion of the wheels requires optimization [1]. The incorporation of multiple propulsion elements e.g. the combination of an ICE and electrical motor (EM) in hybrid vehicles or EM's on both front and rear axles in an all-electric vehicle is an upcoming field of study since EM's only recently found their way to the general consumer and combining multiple ICE's in a passenger car was never really considered a viable design methodology. Many efficient heuristics are in place for the power flow control in vehicle electrification by means of energy management strategies of the storage technology [2] and the EM propulsion [3]. Next to the control, sizing of the components [4] within this large scale mechatronic system can be performed in a model-based manner where the control strategies need to be incorporated in the analysis [1].

In this study an all-electric drivetrain including two EM's is considered. The proposition of translating the optimization statement to a convex minimization problem is explored so to efficiently assess the optimal operational set points within the drivetrain.

POWER FLOW IN VEHICLE ELECTRIFICATION

Drivetrain modelling and power flow

Figure 1 depicts the considered drivetrain. A battery stack functions as a storage buffer for electrical energy. The voltage originating from the battery stack drops in a nonlinear fashion depending on the actual state of charge (SOC). A buck-boost converter is able to control the output voltage of the incorporated DC-bus to a value below or above the input voltage of the converter, buck and boost mode respectively, imposed by the battery stack. In order to supply the electric motor with a three-phase voltage system, a voltage source inverter is required. Next to this, a voltage source invertor (VSI) is well suited to implement torque control measures, i.e. direct torque control (DTC). Finally the electric machines provide the necessary output power. Modeling of the different components is carried out with the aim of providing a sufficient level of detail in order to incorporate dynamic phenomena but with a special focus towards a modular implementation for simulations. State-space models inhibit the dynamical interaction of internal state variables and facilitate a straightforward implementation in a simulation environment, due to their focus on input-output relations and can inhibit the complex interactions between various energy domains. A mean value model of the high frequency switching buck-boost converter overcomes the necessity of simulating the drivetrain by time steps smaller than said switching periods while maintaining the convertor's dynamics controlled by e.g. PI(D) control.

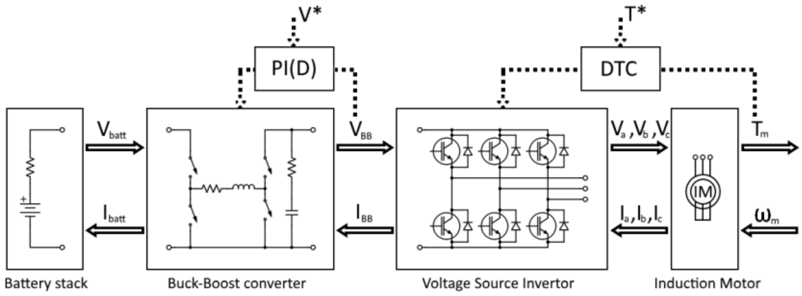

Figure 1. Studied drivetrain containing a battery stack, buck-boost converter, voltage source invertor and an induction motor.

Optimal torque set points by convex optimization of the loss model

Convex optimization allows for efficient solutions to minimization problem statements but do require a translation of the considered optimization problem to an equivalent set of convex minimization objectives. Convexity of the losses cannot be guaranteed in advance but this assumption proves to be very well applicable in a dynamical context when incorporating a realistic representation of the losses, i.e. switching losses, conduction losses, resistor losses and mechanical friction. A mapping of the losses under different circumstances, i.e. various expected torque distributions based on the considered load, allows for a time-efficient approximation and optimization of the occurring loss mechanisms during operation. Convex optimization of the loss models by means of [5] was implemented (for estimating the torque set points T* in Fig. 1). Due to the convex optimization formulation, T* can be efficiently calculated giving rise to the dynamically varying stator voltage and currents depicted in Fig. 2 for variable input loads to the drivetrain. When considering 7 loss functions, 14 constraints and with 500 (1000) time steps as the considered time horizon: 18 (22) iterations are required for the torque set point optimization with CPU-time of 27s (85s) on a regular laptop computer. Convex mapping of power flow dependencies allows for accurate dynamic control using larger time steps, thus increasing the time horizon. The applicability of the convex solver in the optimization of the torque distribution over the motors is enabled using the approach and furthermore makes the sizing of the components within the considered system tractable.

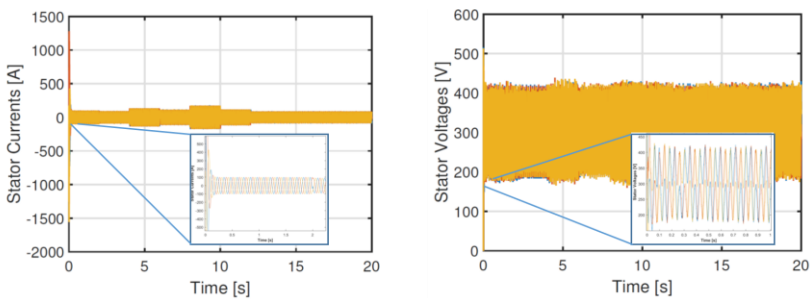

Figure 2. Stator currents (I_a, I_b, I_c) and voltages (V_a, V_b, V_c) over time through direct torque control with the provided torque set points.

CONCLUSIONS

Model-based convex optimized torque set points in a drivetrain consisting of a pair of induction machines, battery stack, buck-boost convertor and voltage source invertor are calculated. The approach is able to efficiently assess the set points compared to nonlinear programming strategies. We mainly considered the optimization for energy efficiency purposes but this can be extended towards other performance criteria.

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