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## **Control Strategy of Energy Flow in Hybrid Propulsion System with Super-capacitor**

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### **Abstract**

The article discusses problem of energy flow in serial hybrid propulsion system with super-capacitor energy storage with respect to robust control and stable behaviour of all the drive. The simulation model in MATLAB/Simulink of serial hybrid vehicle with super-capacitor is presented. Theoretical results are experimentally verified of physical model.

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*Keywords: hybrid electric vehicle, DC/DC converter, LQR controller*

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### **1 Introduction**

Modern lithium-ion batteries have been associated with some explosions and fires in electric vehicles. In many cases the reason is high charging or discharging current. Therefore sophisticated battery management system current enabling uniform cell voltage distribution is required. In case, when high current is needed, power losses due to battery internal resistance are rapidly increased and battery temperature increase as well. To eliminate this phenomena, additional high dynamics and high power source of energy is needed. The super-capacitor seems to be suitable booster for this purpose. Its relatively small energy density to compare with chemical battery is negligible due to its function like "short time source" or "short time accumulator" in case of vehicle accelerating or decelerating.

Super-capacitors are electrostatic devices and its switchover from discharging to charging regime is quicker to compare with chemical batteries. They can be fully discharged for transport and maintenance. Their behaviour is more predictable and they are more tolerant of faults and damage. In the past, they are not so popular because they are expensive and their electricity per unit of

volume or weight is much lower to compare with chemical cells.

Over all previous shortcomings super-capacitors are able to operate with guaranteed life of up to ten years and actual life of over 20 years. Safety is now much more of an issue, with regulations tightening in this respect. Low maintenance is also sought in order to reduce down time and scope for error.

For emergencies such as electric backing up regenerative brakes in a hybrid car super-capacitors are now specified because they are reliable. But not only for backing up of regenerative brakes, but also for main electric car drive boosting is super-capacitor acceptable energy storage. Main role in this drive plays robust super-capacitor charging and discharging control system and sophisticated short time energy needs prediction.

Following article present simulation and experimental study of serial hybrid drive with electric generator driven by internal combustion engine (ICE) and stabilized by super-capacitor and bi-directional buck-boost convertor.

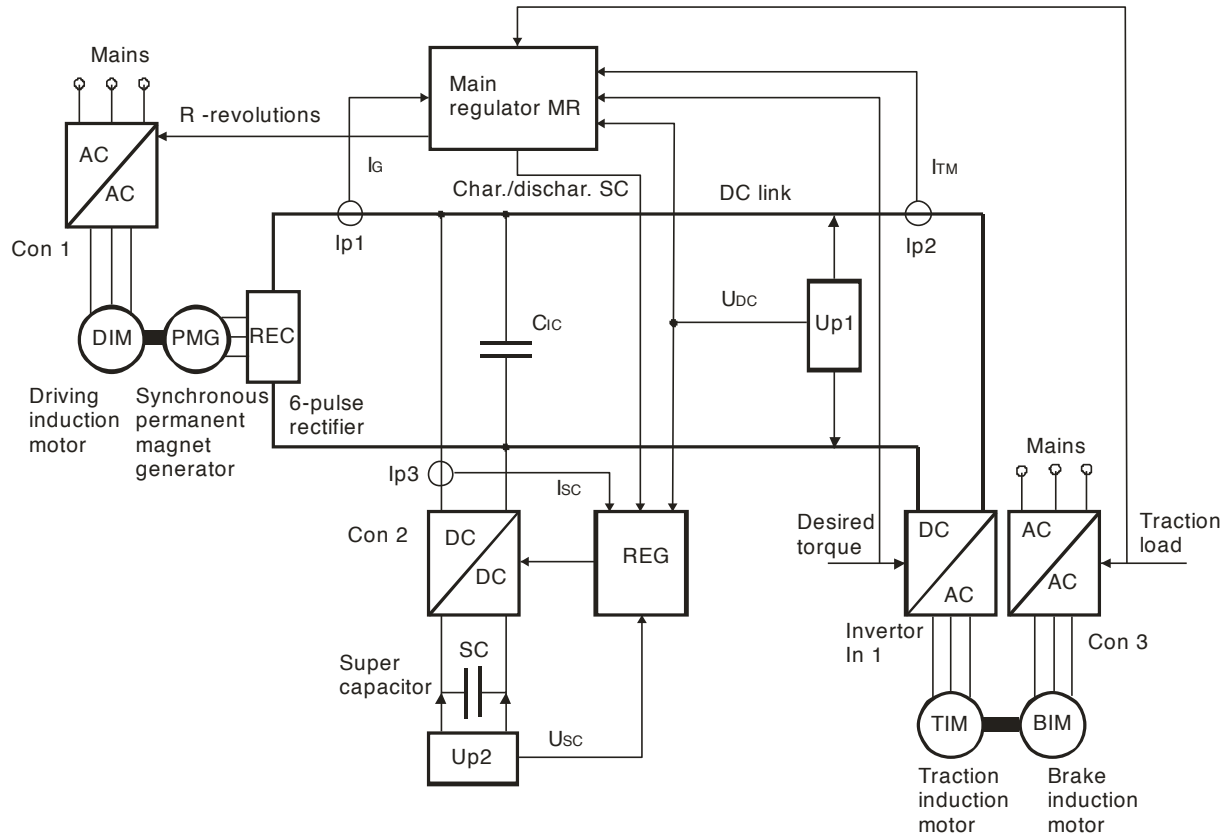


Figure1: One-column figure

## 2 Basic topology of hybrid drive

The hybrid drive topology is serial hybrid with super-capacitor storage. Main source of electricity is synchronous permanent generator (PMG), powered by ICE which is in physical model substituted by driving induction motor (DIM). AC voltage generated by synchronous permanent magnet generator (PMG) is rectified by the three-phase 6-pulse rectifier (REC) and connected to the DC intermediate circuit (DC link). To the DC link via DC/DC converter (Con 2) is connected super-capacitor (SC) and DC/AC inverter (In1). Inverter In1 supplies traction induction motor (TIM). The load of hybrid drive is represented by brake induction motor (BIM), supplied by frequency converter (Con3). Braking system is supplied from the power line (Mains). Block diagram of hybrid drive is depicted on Fig.1.

Needed parameters for control function are measured by voltage probes Up1, Up2, current probes Ip1, Ip2 Ip3. Needed feed-backs for induction motors controls are included and are not especially depicted. Global control is provided by means of main regulator (MR) id dependence on desired torque (input value to

In1) and traction load (input value to Con3). The control algorithm respected border working conditions of PMG and state of charge of SC.

## 3 Philosophy of control algorithm

The goal of optimal control is the lowest consumption of ICE with respect to power limitations (i.e. max. super capacitor capacity, max. power of traction motor, etc.). One objective of energy management system is to control electrical energy flow from or to super capacitor with the aim to minimize the fuel consumption and pollutant emissions. The energy management is an optimal control problem and minimize an integral over an extended time period of driving cycle. The electrical power of ICE is defined as

$$P_{ICE}(t) = P_{MECH}(t) + P_{SC}(t) \quad (1)$$

where:  $P_{MECH}(t)$  is vehicle mechanical power and  $P_{SC}(t)$  is the electrical power of supercapacitor.

The mechanical power depends on the vehicle mass, rolling resistance, aerodynamic drag and the road angle. The electrical power of super capacitor is limited by maximal allowed. super capacitor voltage and charging or discharging current. Accumulated energy depends on the SOC (state of charge).

The main task of energy management is to calculate how the output electrical power is shared between  $P_{ICE}$  and  $P_{SC}$  in order to minimize the fuel consumption with respect of super capacitor capacity limitation. The fuel consumption over a driving cycle is an integral cost which globally is defined as

$$\min J = \int_{t_0}^{t_f} P_{ICE}(t) dt = \int_{t_0}^{t_f} \dot{m}_f(\omega_{ICE}, T_{ICE}, t) dt \quad (2)$$

where:  $\omega_{ICE}$  is the engine speed,  $T_{ICE}$  is the torque produced by engine and  $[t_0, t_f]$  is time period of driving cycle.

The energy management objective is to accomplish following conditions

$$\begin{aligned} SOC_{min} < SOC < SOC_{max} \\ \omega_{ICE,min} < \omega_{ICE} < \omega_{ICE,max} \\ T_{ICE,min} < T_{ICE} < T_{ICE,max} \\ P_{SC,min} < P_{SC} < P_{SC,max} \\ P_{TIM,min} < P_{TIM} < P_{TIM,max} \end{aligned} \quad (3)$$

where:  $P_{TIM}$  is mechanical power of traction induction engine (TIM).

## 4 Simulation model

The simulation model in MATLAB/Simulink has been inspired using schema in the fig. 1 and the

schema is shown in the fig. 2. The model includes 4 main parts:

- Block ICE + PMG
- Block DC/DC + SC
- Block TIM
- Block Main controller

The DC link voltage is regulated on the value 200 V. DC bus output is connected to the Block TIM and to the Block DC/DC + SC. Vehicle is simulated by Vehicle load simulation block where the output is torque on wheels.

## 5 Simulation results

The next experiment has been designed for presentation of simulation model. The voltage on DC link has to be from 150 V to 230 V. At time = 0 s the reference DC link voltage was 200 V. At the time 0.5 s the TIM speed increased with the slope 1000 1/min per 1 s to the maximal value 1000 1/min. At the time 5 s the load with the slope 5 Nm per 1 s to the maximal value 10 Nm was connected. The graphs in the fig. 3 present the simulation results.

On the left side is the graph Power = f (Time) and on the right side is the graph Voltage = f (Time). The voltage is in the range 150 V and 230 V which is the maximal possible values.

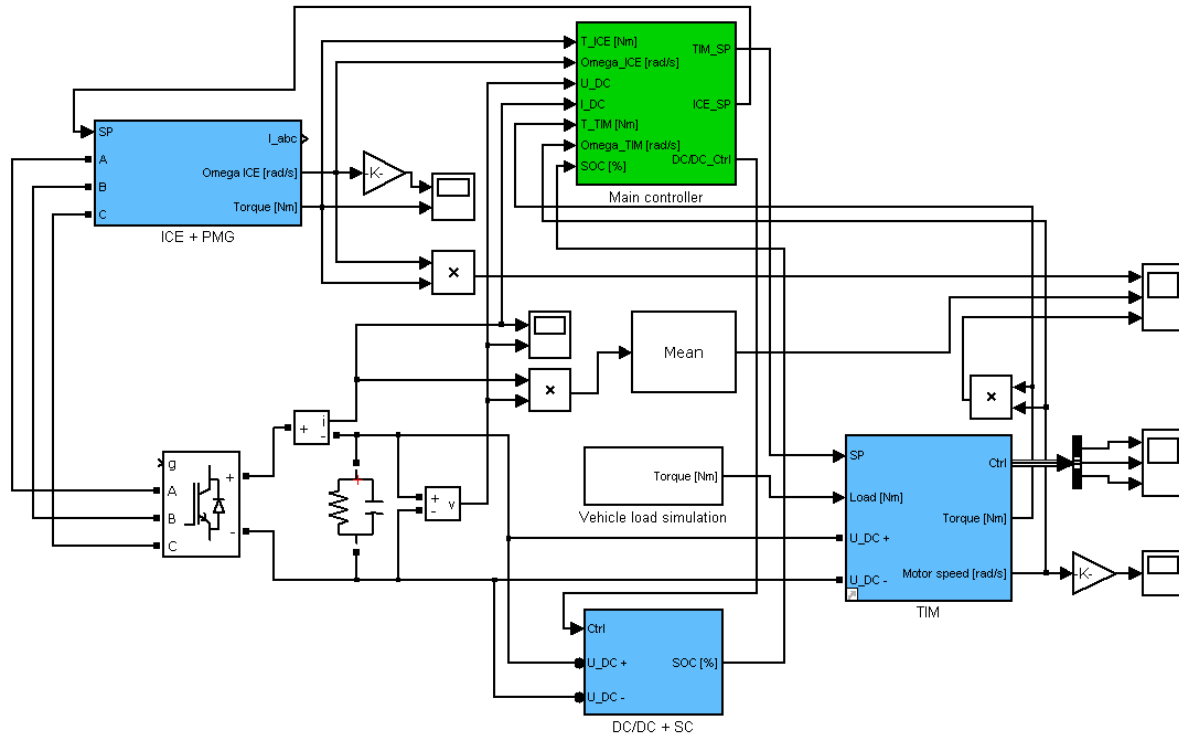


Figure1: One-column figure

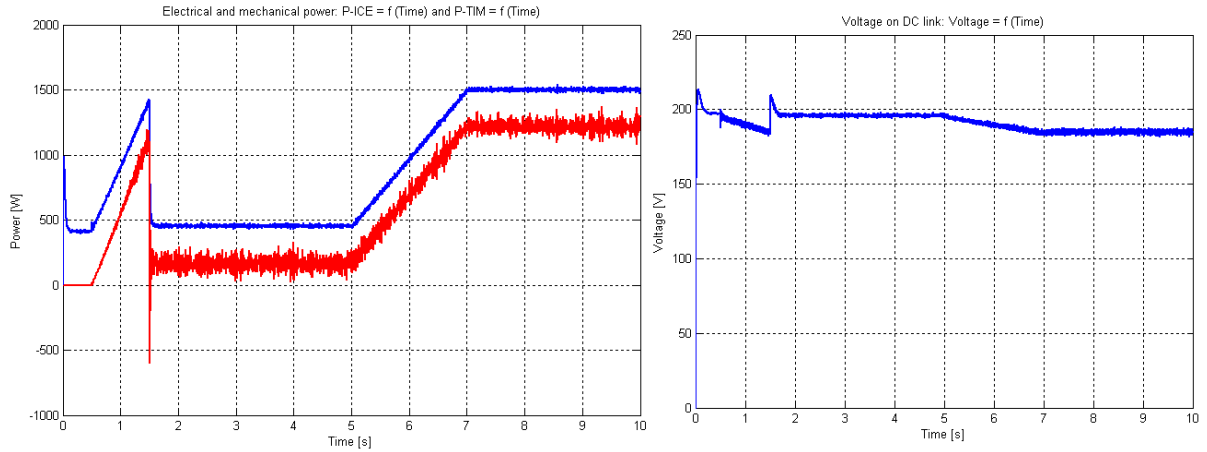


Figure 3: Simulation results

The graph Power = f (Time) represents output power of ICE + PMG (blue colour) and mechanical power of TIM (red colour). The difference between these two graphs is a power lost on the power electronic and electric machines and a power used for super-capacitor charging.

## 6 Measured results

The proposed algorithm was realized on the prototype on the series hybrid test bed (fig. 1). The super capacitor DC/DC converter was controlled by NXP processor, which offers:

- 72Mhz 32Bit Processor
- 16MB RAM
- 4.5MB FLASH
- 76 GPIO Pins
- 39 Interrupt Inputs
- 2 SPI (8/16bit)
- I2C
- 4 UART
- 2 CAN Channels
- 10Bit Analog Inputs.
- 6 PWM

That is enough computational power to execute LQR control algorithm for the DC/DC converter. The LQ controller creates the state-feedback law  $u = -Kx$  which minimizes the quadratic cost function

$$J(u) = \int_0^{\infty} (x^T Q x + u^T R u + 2x^T N u) dt \quad (4)$$

With the respect of the system dynamics

$$\dot{x} = Ax + Bu \quad (5)$$

The results of the system are depicted in the fig. 4.

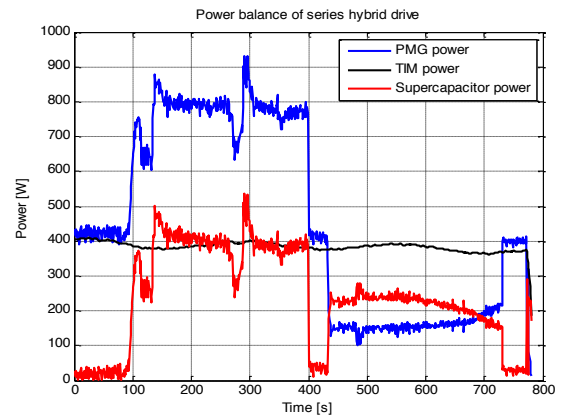


Figure 4: Power balance in series hybrid drive

From time 0 to 100s, the super capacitor is switched off and the whole power of the DIM is consumed by TIM. In the time interval 100 – 400 s the super capacitor turned on in charging mode. In the time 130 s and 280 s the DIM has not produced enough power to change super capacitor therefore the LQR controller limits the power of DC/DC converter. In the time 295 s the power delivered by DIM has arisen therefore the DC/DC converter controller has increased the power to the super capacitor. In the time interval 430 – 740 s the super capacitor was switched to the boost mode that means the energy was taken from the super capacitor. The LQR control algorithm held the value of the power on the value that was required for the balanced DC link voltage, which is obvious from the figure 5.

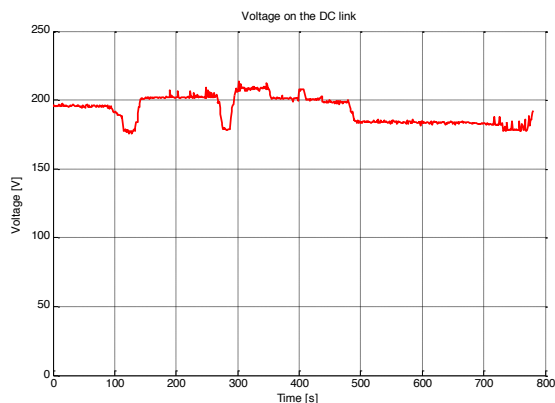


Figure 4: Power balance in series hybrid drive

## Conclusion

Utilization of the series hybrid drive with the super capacitor converter in the DC link control algorithm has been presented. The aim of the super capacitor DC/DC converter connected to the DC link of the hybrid was to store and supply the energy. For this purpose the DC/DC converter must operate in both buck and boost mode. This can be easily achieved by one IGBT module however the power delivered by the converter depends on the operation mode. The adaptive LQR controller finds its place. Both simulation and measured results (fig. 3, 4, 5) show that the LQR controller reacts with fast and without overshoot.

The presented results looks very promising, however the real impact of the proposed control strategy will be evaluated after the measurements on the real hybrid car prototype in our research centre.

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