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Mild-Hybrid Traction System Based on a Bidirectional Half-Bridge Interleaved Converter and a Three-Level Active NPC Inverter-Fed PMSM

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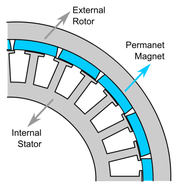
The Topic

In this paper a practical and original solution for a **mild-hybrid traction system** is proposed. The proposed system architecture is a **two-stage bi-directional power converter** controlled by digital signal controllers. The electric surface permanent magnet (SPM) synchronous machine is fed by a three-phase three-level active neutral point clamped (NPC) inverter. The middle dc bus feeds a four-phases interleaved half-bridge converter connected to the battery pack.

System Overview

Indeed the proposed system can be used also as stand-alone battery charger and pure electric vehicles. The **power rating of the electric machine is about 4 kW**. The **battery voltage level** is a standard value (**28 V**), leading to a rated current of about 150 A. The **intermediate dc bus voltage** has been fixed to **150 V** .

Electric SPM machine



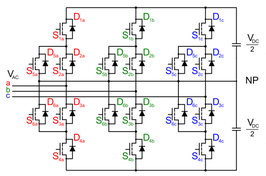
Sketch of stator laminator and PM in the rotor

ELECTRIC MACHINE PARAMETERS.

Parameter	Symbol	Value
Pole number	$2p$	18
Slot number	Q	27
External stator diameter	D_e	156 mm
Stack length	L_{stk}	35 mm
Rated torque	T_N	10 Nm
Rated phase current	I_N	25 A_{rms}
Rated phase voltage	V_N	60 V_{rms}
Phase resistance	R_s	75 $m\Omega$
Phase inductance	L_s	0.23 mH
Rated speed	n_{max}	4000 rpm

- **SPM synchronous machine** (high torque density).
- **Outer rotor** (space saving).
- **Tooth-wound** (reduce the copper weight and also cost and Joule losses).

Three-Phase Active NPC Inverter

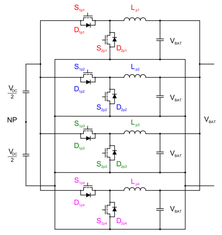


ACTIVE NPC INVERTER PARAMETERS.

Parameter	Symbol	Value
Switching frequency	F_{SW}	20 kHz
Rated dc bus voltage	V_{DC}	150 V
Rated ac phase voltage	V_{AC}	60 V_{rms}
Rated ac phase current	I_{AC}	35 A_{rms}

- The **active NPC inverter** (additional active switches in anti-parallel to the clamping diodes).
- The additional switches make **new switch states** (they allow a specific utilization of the upper and lower path of the neutral point, thus affecting the distribution of conduction and switching losses).

Four-Phase Interleaved Half-Bridge Converter



INTERLEAVED HALF-BRIDGE PARAMETERS FOR EACH PHASE.

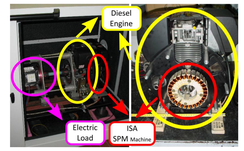
Parameter	Symbol	Value
Number of phases	N	4
Switching frequency	F_{SW}	50 kHz
Maximum dc bus voltage	V_{DC}	150 V
Maximum battery voltage	V_{BAT}	30 V
Maximum battery current	I_{BAT}	32 A
Output Inductance	L_p	50 μH
Output Inductance Resistance	R_{L_p}	9 $m\Omega$

- The **battery side has high current** .
- Stage is **composed by 4 phases** (good compromise between complexity/cost and efficiency).
- **Interleaved converter** (lower current ripple and increase the output frequency).

Experimental Test Bench

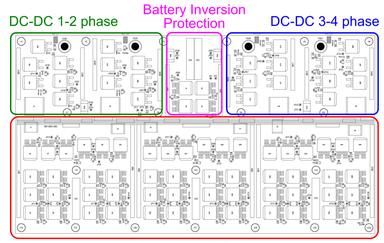
INTERNAL COMBUSTION ENGINE PARAMETERS.

Parameter	Value
Type combustion cycle	Diesel
Number of cylinders	Single
Piston displacement	400 cm^3
Maximum power	4 kW
Maximum speed	4000 rpm
Minimum speed	800 rpm
Starting torque	18 Nm



The test bench has been realized to test the performance of the proposed electronics and control.

Prototype Board



Layout of the power converter board

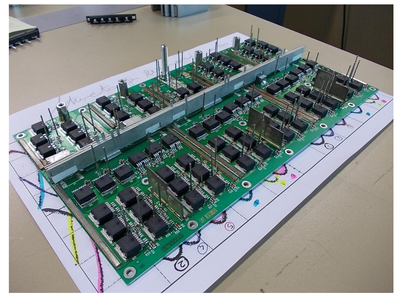
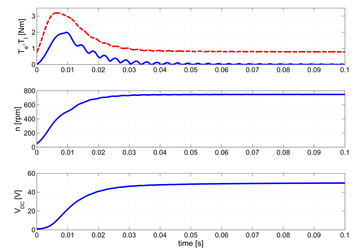


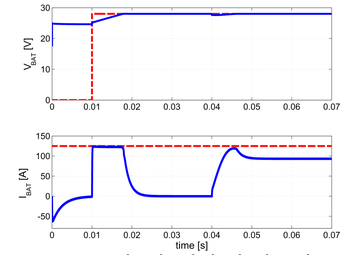
Photo of the power converter prototype board

Proposed power conversion system is still under development.

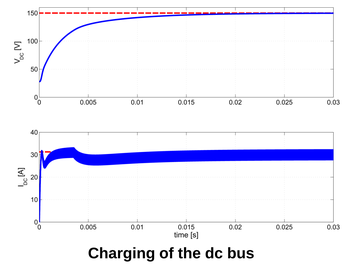
Simulation Results



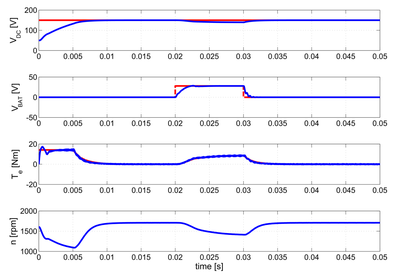
Thermal engine startup and pre-charge of dc bus



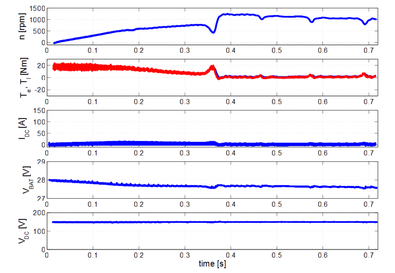
Battery charging during buck mode



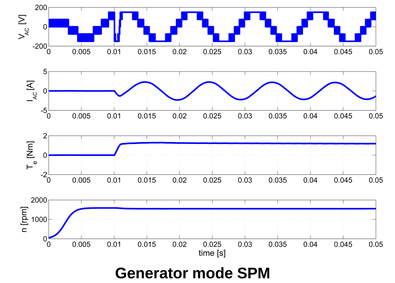
Charging of the dc bus



Boosting of dc bus and load power demand



Full startup of diesel engine

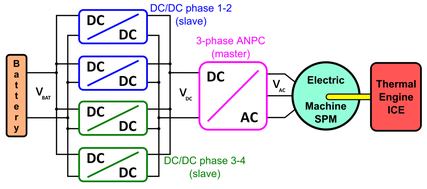


Generator mode SPM

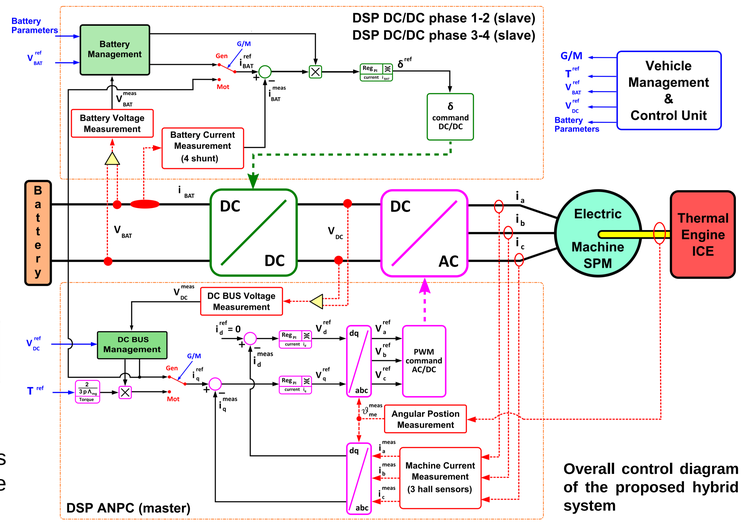
Controller Scheme

The proposed control system is equipped by **three independent but interacting digital signal controllers:**

- **1 MASTER**: ANPC and SPM machine control algorithms.
- **2 SLAVE**: each two-phase interleaved dc/dc converter control.



There are **two operating modes** ("G/M") is controlled by a logical state provided by the vehicle management and control unit :



Overall control diagram of the proposed hybrid system

- **Motoring mode**: power is transferred from the battery to the motor drive (during startup or a torque boost to the ICE), the dc/dc converters are operated in boost mode and dc bus voltage is controlled t o the rated value, while the electric machine is speed or torque controlled.
- **Generating mode**: the (braking) torque of the electric machine is controlled in order to maintain a constant dc bus voltage, while the dc/dc converters are controlled in buck mode to regulate battery current. Reference battery current calculation and control of battery voltage are performed inside the"Battery Management" unit.

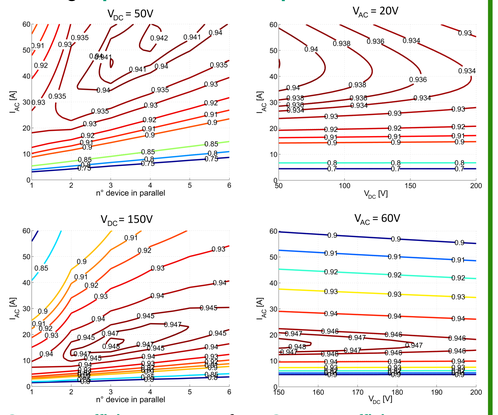
Design Choices

$$P_{SW} = \frac{1}{2} I_D V_D (t_{rise} + t_{fall}) F_{SW}$$
$$P_{ON} = R_{ON} I_D^2$$

SWITCH PARAMETERS OF CONVERTER AT 100^o C.

Parameter	Value	
	dc/dc converter	NPC converter
Type of switch	Mosfet	Mosfet
Maximum voltage	200 V	100 V
Rated current	50 A	130 A
On resistance	35 $m\Omega$	6.5 $m\Omega$
t_{rise}	0.8 ns/A	0.7 ns/A
t_{fall}	1.8 ns/A	1.4 ns/A

The **power consumption of converter control electronics** can also be included and are estimated in the worst case as **40 W** when driving **3 power devices in parallel**.



Constant efficiency maps of total converter with different number of device in parallel.

Constant efficiency maps in the plan current versus dc bus voltage.

Conclusions and Future Work

- A conversion system suitable for hybrid and/or full electric vehicles is proposed in this paper. It is based on a surface permanent magnet synchronous motor drive, a 3-level ANPC inverter and bidirectional half-bridge interleaved converter.
- Optimization and advantages of the considered system architecture have been analyzed through simulations.

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