A Novel Enhanced Connection of AC/AC Powertrain for HEV – Modelling and Simulation Results

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Abstract. *The paper deals with a novel enhanced connection of AC/AC powertrain for Hybrid Electric Vehicles (HEV). The substantial contribution of such a connection is the absence of 4QC auxiliary converter needed for autonomous and hybrid operational modes and its compensation by power-lesser 0×5 matrix converter. The main advantages of a simplified connection are, beside smaller auxiliary converter sizing, also possible better efficiency of the HEV powertrain. So, powertrain operation in autonomous traction accu-battery modes uses direct 0×5 configuration of traction 3×5 M×C matrix converter, and in hybrid modes of Internal Combustion Engine (ICE) and accu-battery uses besides traction 3×5 M×C matrix converter the auxiliary 0×5 matrix converter. Modeling and simulation using Matlab-Simulink environment of traction powertrain configuration in autonomous modes are presented in the paper as well as all simulation experiment results.*

Keywords

0×5 matrix converter, 3×5 matrix converter, AC/AC powertrain, a bidirectional switch, electric drive, five-phase induction motor, hybrid electric vehicle, internal combustion engine, modeling and simulation.

1. Introduction

Hybrid Electric Vehicles (HEV) have an important role in the automotive industry as well as in the national economy and also in transport and traffic services. The majority of series HEV powertrains use front-end converter system with a DC-voltage interlink [1], [2], [3] and [4]. It has been shown in the paper by comparing of a matrix converter (M×C) and VSI converter with an active front end for induction motor drive that the matrix converter's semiconductor losses are smaller at full load operation for the same silicon area in both converters in the paper. A one-third reduction of the device current rating of the M×C is possible resulting in comparable thermal device stress, [5] and [6]. The overall passive component count and rating are only slightly better for the M×C but the absence of bulky smoothing capacitor is evident what is presented in [7]. Therefore, the AC/AC powertrain with matrix converter was designed to improve the energetic efficiency of HEV, [7] and [8]. Regarding the number of phases, if the number of phases of the motor is three (no more) then it is not possible to connect both traction motors to one common direct traction converter, [9], [10] and [11].

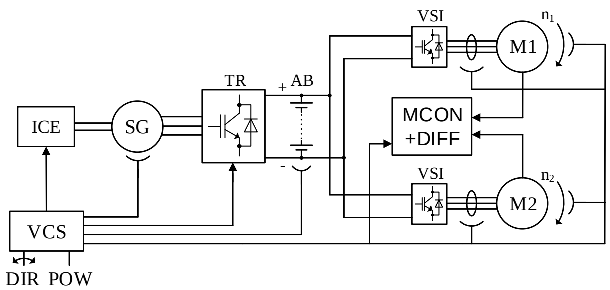


Fig. 1: Classical series HEV with two VSI converters two motor wheels and electronic differential.

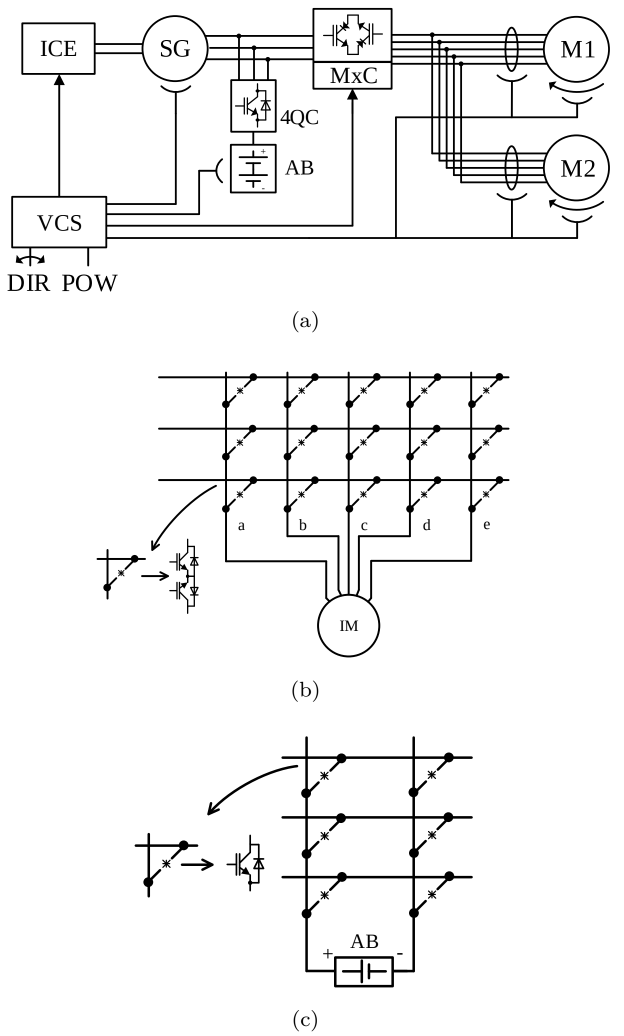
ICE - Internal Combustion Engine, SG - Synchronous Generator, TR - Traction Rectifier, AB - traction Accu-Battery, VSI - Voltage Source Inverter, TM1,2 - Traction Motors, VCS - Vehicle Control System, MCON - traction Motors Control.

Configuration with motor-wheels allows flexibility of the car and removes the central drive motor and associated transmission parts of the propulsion system of the vehicle. The main advantages of the electric motor in the wheel are adjustable traction and individual braking torque with high precision without ingestion gearbox, drive shaft, differential gear and other complex and heavy parts of power transmission, [3] and [4]. One of such a traction system is shown in Fig. 1.

2. Direct AC/AC Powertrain

Structural scheme of HEV with AC/AC powertrain is shown in Fig. 2 As it has been shown in [4] and [5], the good compromise among a different number of phases traction generator and traction motor is a three-phase generator and a five-phase motor that means [3×5] direct converter. Such a configuration of the AC/AC powertrain makes possible both pure electric operating modes and/or pure engine mode, as well as hybrid mode: the vehicle is propelled by Internal Combustion Engine (ICE) and accu-battery energy in parallel operation [7].

Note, to provide for full autonomous HEV operation from Accu-Battery AB (e.g. traction), the sizing of 4QC converter should be done for nominal traction power of two Traction Motors (TM).



(a) (b) (c)

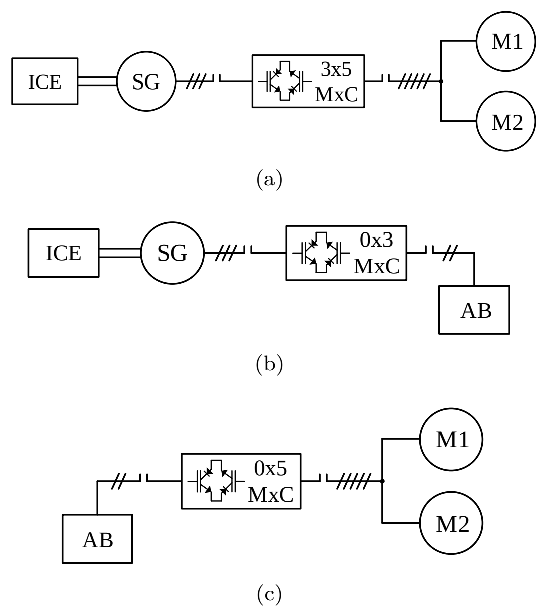
Fig. 2: Direct AC/AC series HEV with one M×C converter/one auxiliary 4QC converter and two traction motors with independent control a), and topologies of M×C and 4QC converters with IGBT switches b) and c).

3. Novel Enhanced AC/AC Powertrain

The configuration of novel simplified AC/AC powertrain shown in Fig. 4 can be applied for following possible operation modes:

- traction drive/brake:/l ICE-SG-ACAC-5PIM // 5PIM-ACAC-SG-ICE (Fig. 3(a)),
- traction drive/brake/charging: AB-ACAC-5PIM // 5PIM-ACAC-AB (Fig. 3(b)),
- starting-up/charging: AB-ACAC-SG-ICE // ICE-SG-ACAC-AB (Fig. 3(a)).

Possible operational models of novel simplified AC/AC powertrain are shown in Fig. 3.



(a) (b) (c)

Fig. 3: Possible operational model of novel enhanced AC/AC powertrain: (a) traction drive/brake: ICE-SG-ACAC-5PIM // 5PIM-ACAC-SG-ICE, (b) traction drive/brake/charging: AB-ACAC-5PIM // 5PIM-ACAC-AB, (c) starting-up/charging: AB-ACAC-SG-ICE // ICE-SG-ACAC-AB.

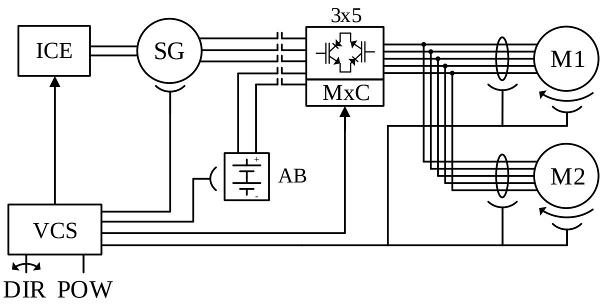
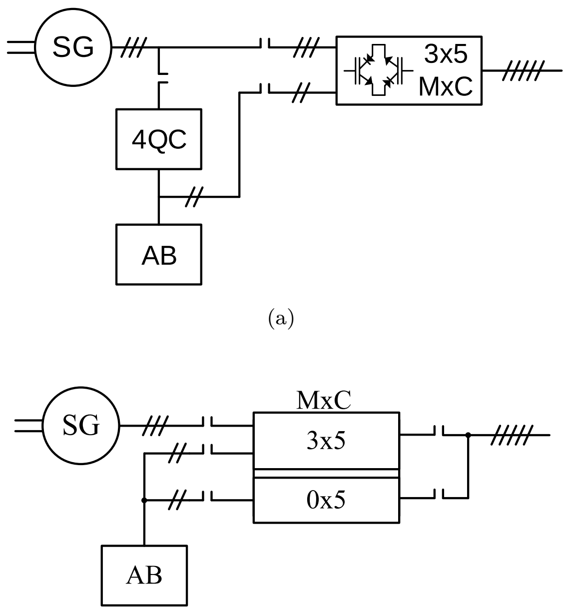


Fig. 4: Novel enhanced AC/AC series/parallel HEV with one M×C converter and two traction motors with independent control.

3.1. Hybrid Operational Mode of HEV Powering

Parallel operation of ICE and traction Accu-Battery (AB) is possible using three-phase four-quadrant converter 4QC, Fig. 5(a), [8]. If the 4QC converter is omitted, the novel scheme of HEV powertrain, Fig. 5(b), makes possible the parallel operation of ICE and AB using 0×5 M×C converters. It gives sophisticated solution making possible parallel as well as the autonomous operation of ICE and AB. Such a configuration can be easily derived from that main traction converter 3×5 M×C.

As it deals with parallel operation, such an HEV is series and parallel vehicle. The sizing of paralleling converter (4QC or 0×3 M×C) is then done just for the differential power of traction motors and ICE. Practically, it is used during the acceleration mode.



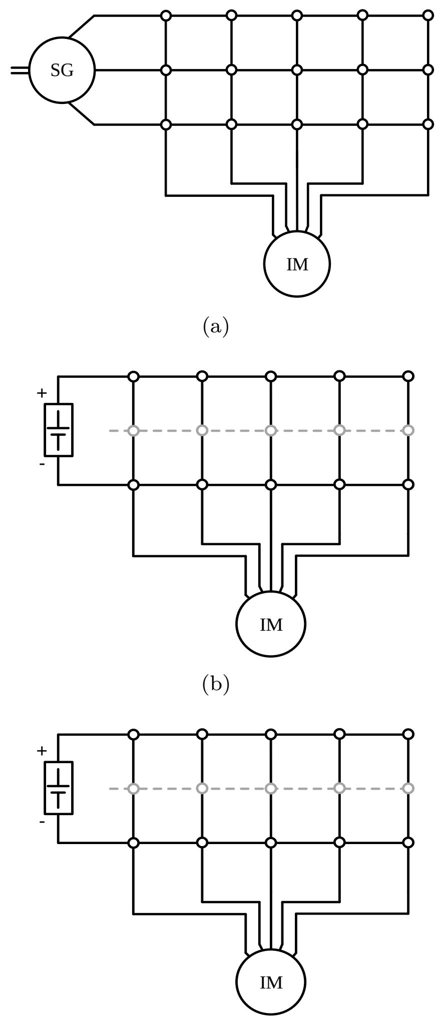
(a)

(b)

Fig. 5: Hybrid operation possibility: parallel connection of ICE and AB, (a) using a 4QC converter and (b) parallel connection of ICE and AB using 0×5 M×C converter.

4. Modeling and Simulation

The ICE has been modeled by DC motor with separate excitation system. The control scheme of that substitution model is given in works [8], with help of [12], [13] and [14]. Besides, just one traction motor has been taken into account, independent control of two traction motors has not been used in these simulations. Possible configurations of AC/AC converter for different operational traction modes are shown in Fig. 6.



(a)

(b)

(c)

Fig. 6: The configuration of M×C converter for different operational modes-5PIM: (a) traction drive powered by ICE/braking into ICE, (b) traction drive powered by AB Accu-Battery/braking (charging) into AB, (c) start-up of ICE powered by AB Accu-Battery/charging of AB by ICE.

There are three basic configurations:

- traction drive powered by ICE/braking into ICE (Fig. 6(a)),
- traction drive powered by AB Accu-Battery/braking (charging) into AB (Fig. 6(b)),
- start-up of ICE powered by AB Accu-Battery/charging of AB by ICE (Fig. 6(c)).

Simulation models of matrix converters (direct [15] or indirect models [7] and [16] are known, as well as dynamical models of 5PIM motors [9] and [17] and models of DC separately excited motor [18] and of SG [22].

So, e.g., the vector equations of 5PIM stator voltage gives [8]:

$$u_s = \frac{2}{5}\left(u_a + u_b e^{j\frac{2\pi}{5}} + u_c e^{j\frac{4\pi}{5}} + u_d e^{j\frac{6\pi}{5}} + u_e e^{j\frac{8\pi}{5}}\right) = u_\alpha + j u_\beta, \quad (1)$$

and:

$$\begin{bmatrix} u_a(t) \\ u_b(t) \\ u_c(t) \\ u_d(t) \\ u_e(t) \end{bmatrix} = \begin{bmatrix} u_{m1}(t) & 1-u_{m1}(t) \\ u_{m2}(t) & 1-u_{m2}(t) \\ u_{m3}(t) & 1-u_{m3}(t) \\ u_{m4}(t) & 1-u_{m4}(t) \\ u_{m5}(t) & 1-u_{m5}(t) \end{bmatrix} \left[U^+(t) - U^-(t)\right], \quad (2)$$

where $U^+(t) - U^-(t)$ are fictitious voltages of fictitious DC link of matrix converter [6]. Then one can use a dynamic model of the 5PIM motor as:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} i_s \\ i_r \\ \omega_m \end{pmatrix} = A\begin{pmatrix} i_s \\ i_r \\ \omega_m \end{pmatrix} + B\begin{pmatrix} u_s \\ u_r \\ 0 \end{pmatrix}, \quad (3)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \frac{T_{elmg} - T_{load}}{J_m}. \quad (4)$$

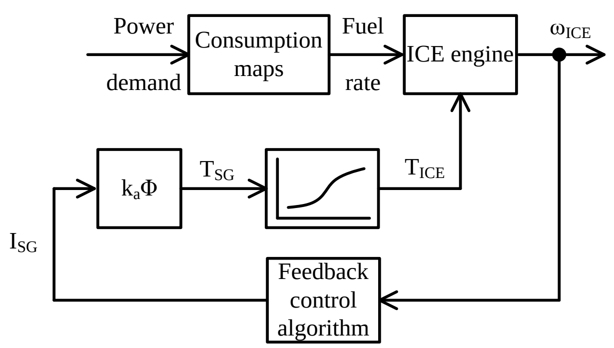


Fig. 7: ICE and PMSG generator control system [12], (model of ICE substituted by DC machine).

The control system for ICE and Synchronous Generator (SG) loop for the gearless system is shown in Fig. 7 Control methods for Induction Motor (IM) using PWM technique can be taken from [15], [19], [20] and [21]. So far, this IM control problem as well as whole HEV control loop, have not been solved in the paper.

The parameters of the powertrain for simulation are given in Tab. 1.

Tab. 1: The parameters of powertrain.

ICE engine (DC motor)	Power (HP)	30
	Nom. speed (RPM)	1750
	Armature voltage (V)	500
	Field voltage (V)	300
3 Ph. PMSG	Power (HP)	11.5
	Nom. speed (RPM)	3000
	Nom. torque (Nm)	27
	DC bus voltage (V)	560
5 Ph. IM	Power (HP)	10.2
	Nom. speed (RPM)	3000
	Nom. torque (Nm)	23

4.1. Simulation Results

Simulation results were performed using Matlab/Simulink and are given in figures from Fig. 8 to Fig. 12. From the amount of possible operation modes, these ones have been modeled and simulated using novel simplified powertrain:

- start-up and traction drive of HEV powered by ICE,
- start-up of ICE powered by AB Accu-Battery using SG as a starter,
- traction drive powered by AB Accu-Battery and braking (charging) moving energy into Accu-Battery AB.

1) Start-up and Traction Drive of HEV

The ICE is starting to idle speed (about 150 rad· s^{-1}). Then, after 3 sec, the traction motor is connected via a synchronous generator and 3×5 matrix converter. The speed of ICE (and SG, too) is increased to requested value and controlled to this value given by the requested value of traction motor or HEV, respectively. Results of this operational mode are shown in Fig. 8. Detailed waveforms of phase currents of traction generator and 5PIM traction motor are given in Fig. 9.

2) Start-Up of ICE Powered by AB Accu-Battery Using SG as a Starter

In the Fig. 10 there is shown start-up of ICE powered by AB accu-battery using SG as a starter. Detailed

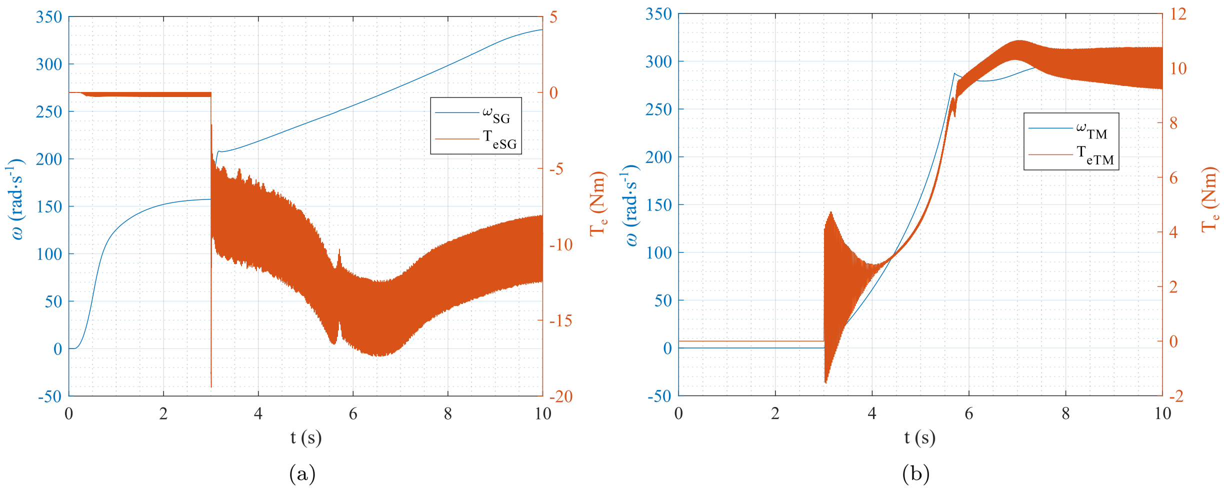


Fig. 8: Details of speed and torque waveforms of SG a) and TM b) during start-up.

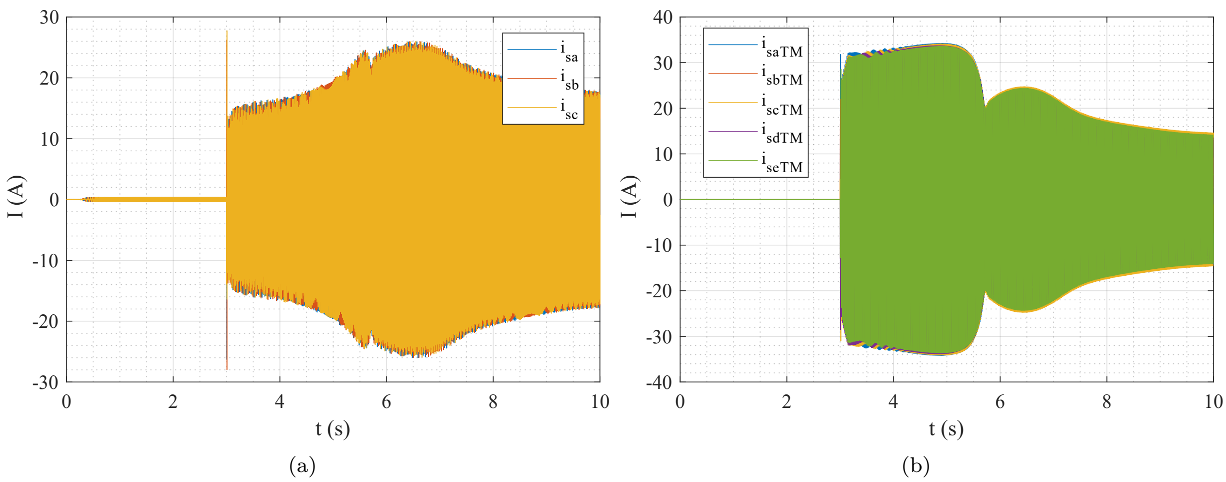


Fig. 9: Details of phase-current waveforms of SG a) and TM b) during start-up.

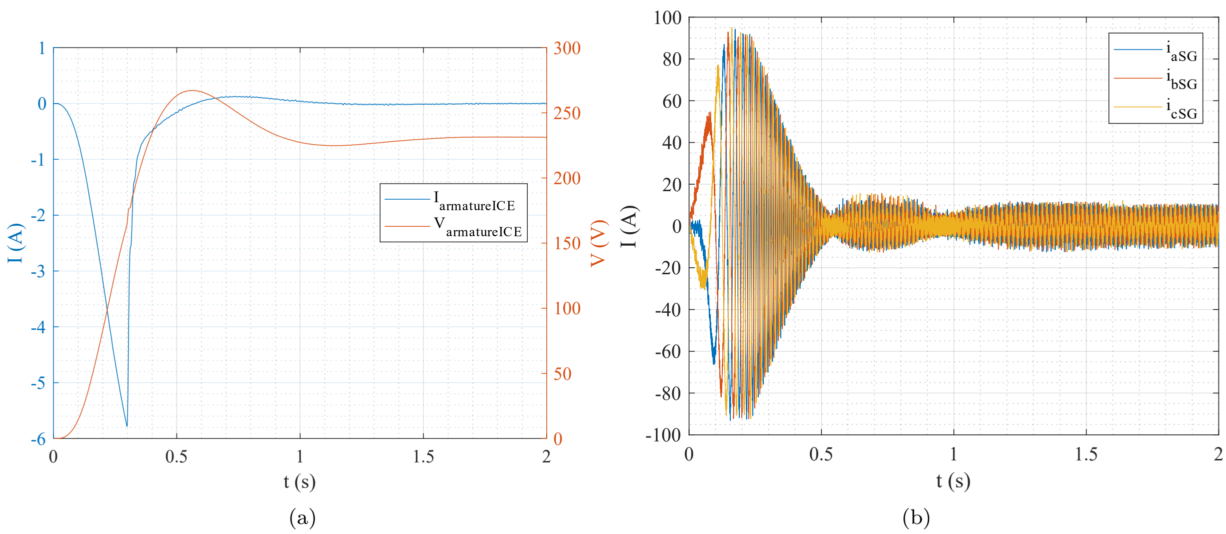


Fig. 10: Start-up of ICE powered by AB Accu-Battery using SG as a starter: current and voltage of DC motor (modeling ICE) a) and phase-current of SG b) – 0×3 M×Cs.

waveforms of SG phase-currents, speed and torque are given in Fig. 11. This operational mode uses 0×3 M×C converter.

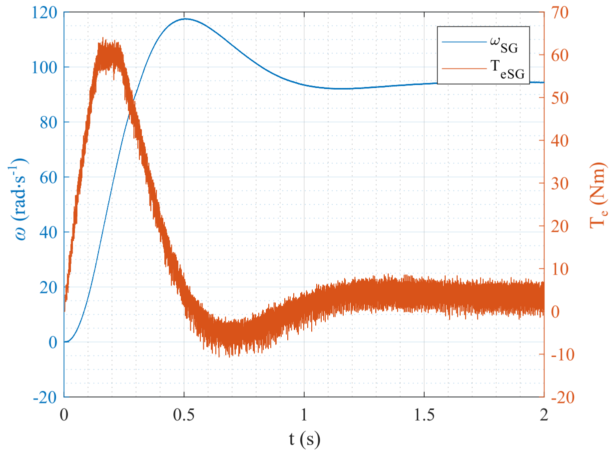


Fig. 11: Start-up of ICE powered by AB Accu-Battery using SG as starter: and details of SG speed and torque waveforms.

This operational mode uses 0×3 matrix converter which can be simply derived from 3×5 M×C converter.

3) Traction Drive Powered by AB Accu-Battery and Braking

Traction and recuperation of TM braking energy by/into accu-battery AB is enabled by use of single 0×3 matrix converter. Figure 12 shows the start-up of TM to nominal or other requested speed and then, at time of 1 sec, traction operation is changed to regeneration, moving energy into the Accu-Battery. The detailed waveforms of electromagnetic torque of the traction motor are given in the Fig. 12.

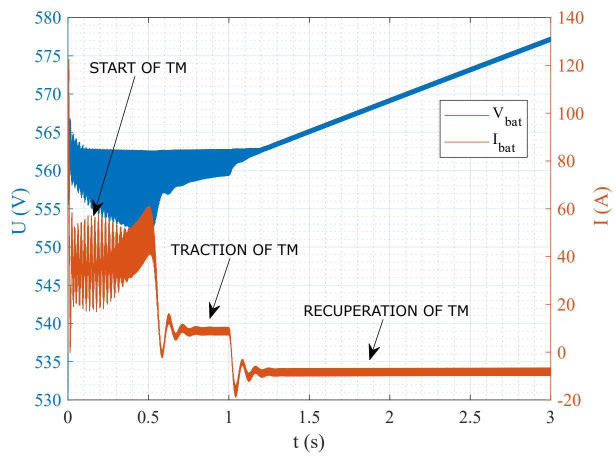


Fig. 12: The course of uAB and iAB during traction- and recuperation of TM braking energy.

Hybrid operation modes have not been modeled and simulated in this paper. Complete powertrain control with both parallel and autonomous modes using the real model of ICE is a demanding issue, anyway, it should be done before the development of HEV.

5. Conclusion

A novel simplified and enhanced configuration of series Hybrid Electric Vehicles (HEV) with AC/AC powertrain has been introduced in the paper. Major advantages of using such AC/AC power transfer with 3×5 M×C and five-phase induction traction motors have been mentioned for their higher torque density, smaller voltage drops, smaller torque ripple, greater efficiency, better fault tolerance and better noise characteristics. The substantial contribution of such a connection is the absence of 4QC auxiliary converter and its compensation by power-lesser 0×5 matrix converter. Autonomous operational modes simulations of HEV powertrain have shown a good functionality of the system. Hybrid modes simulation is rather complex, and it will be, consequently, investigated and published in the next works of the authors.

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