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BASIC COMPARISON AND EVALUATION OF FUNCTIONALITY AC-AC MATRIX CONVERTER CONCEPTS FOR HEV VEHICLE - PART I

The paper deals with the direct AC-AC propulsion system and compares two matrix converter concepts with five-phase traction induction motors (IM) for the hybrid electric vehicle (HEV) including electronic differential. The first one consists of [3x5] matrix converter and [3x1] active PWM rectifier (4Q-converter) for full power performance. The second one comprises one [3x5] matrix converter for full power and auxiliary [0x5] matrix converter for partial output power. Configurations of [3x5] + [0x5] MxC converters with five-phase motor(s) are not analyzed in available literature so far. The advantage of the proposed connection is in supposed higher efficiency of matrix converter then classical VSI one. Part I deals with a theoretical study of converter concepts for hybrid electric vehicle. Based on simulation results the comparison and evaluation of the property and quality of the quantities of different type of the matrix powertrain are discussed in Part II.

Keywords: AC/AC powertrain, 3x5 matrix converter, 0x5 matrix converter, five-phase induction motor, electric drive, 4QC converter, modeling and simulation, HEV vehicle

1 Introduction

The mostly series HEV powertrains use front-end converter system with a DC-voltage interlink [1-5]. Since in-vehicle driving tests for evaluating performance and diagnostic functionalities of engine management systems are often time-consuming, expensive and not reproducible, simulation methods with HIL (hardware in the loop) or SIL (software in the loop) simulators allow to validate new hardware and software automotive solutions.

One of the important questions is the number of phases of the generator and/or traction motor, respectively. If the number of phases of the generator are smaller than three, so the power fluctuation in fictitious DC interlink is rather high [6-7]. Similarly, on the opposite, if the number of phases of the motor is just three (no more) then there is not possible to connect both traction motor to on one common direct traction converter [8-13], Figure 1.

Advantages and operation of a five-phase induction motor are described in [14], its operation under loss of one phase of a feeding source in [15].

Such a configuration of the AC/AC powertrain makes it possible both pure electric operating modes and/or pure engine mode, as well as hybrid mode: the vehicle is propelled by ICE engine and accu-battery energy in parallel operation [1].

Note, to provide of full autonomous HEV operation from accu-battery AB (i.e. traction one), the sizing of 4QC converter should be done for nominal traction power of two traction motors TM.

The mostly powertrains with matrix converters use [3x3] MxC with three-phase IM/SM motors [8, 16-17], except for the author works [6, 18-19] and partially [8]. It is assumed that total efficiency will be higher as classical one because of higher efficiency of MxC then VSI [11], and nearly the same efficiency of [3x3] and [3x5] MxCs [8, 19]. The [0x5] MxC (with partially power) is supposed for parallel operation only, so, the total operational efficiency should be higher.

2 Direct AC-AC matrix converter powertrain without 4QC

The configuration of novel simplified AC/AC powertrain shown in Figure 2 can be applied for following possible operation modes [6, 18]:

- traction drive/brake from/to ICE engine: ICE->>SG->>MxC->>5PIM or, respectively 5PIM->>MxC->>SG->>ICE
- traction drive/brake/charging from/to accu-battery: AB->>MxC->>5PIM or, respectively 5PIM->>MxC->>AB
- starting-up of the engine/charging of the accu-battery: AB->>MxC->>SG->>ICE or, respectively ICE->>SG->>MxC->>AB.

In above modes are followed:

- ICE - internal combustion engine
- SG - synchronouos generator
- MxC - direct matrix converter(s)
- 5PIM - five-phase induction motor(s)
- AB - accu-battery(-ies).

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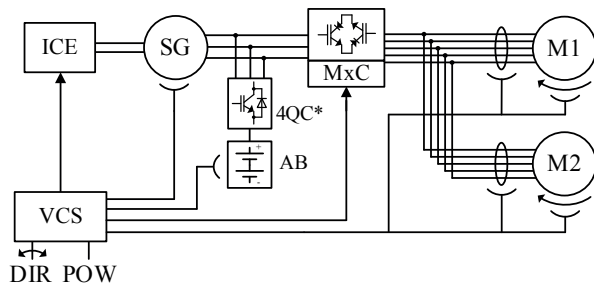


Figure 1 Direct AC-AC propulsion system with one 3×5 matrix converter and parallel connected two five-phase IM traction motors [6]

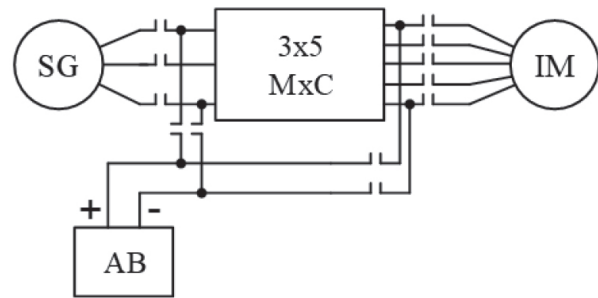


Figure 3 Connection for autonomous modes of HEV

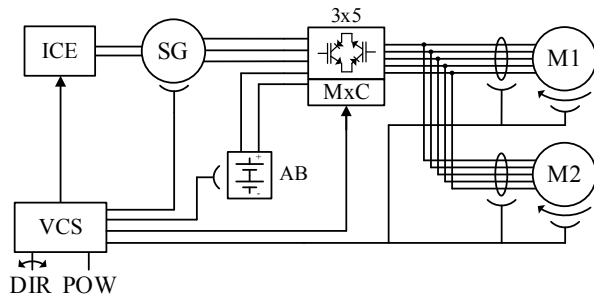


Figure 2 Novel enhanced AC/AC series/parallel HEV with one $M \times C$ converter and two traction motors with independent control

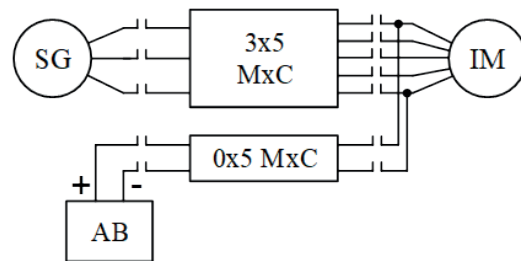


Figure 4 Hybrid parallel operation of HEV of ICE and AB using 0×5 $M \times C$ converter

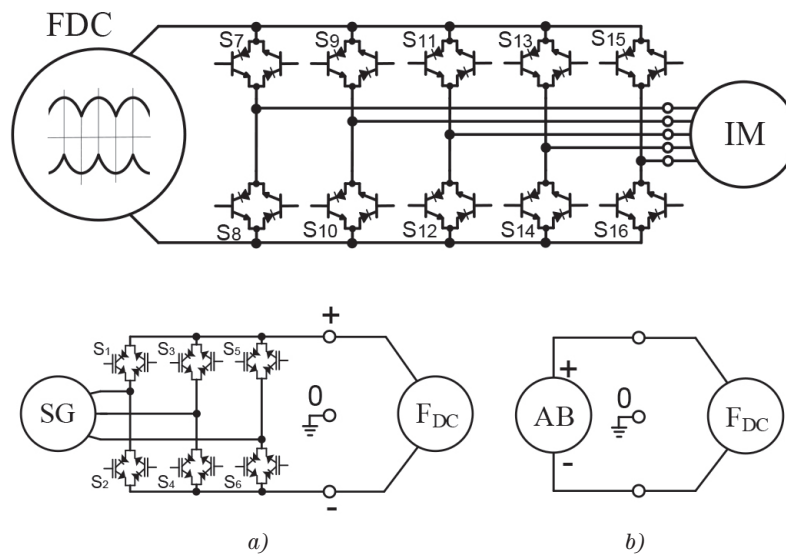


Figure 5 Structural schemes of $M \times C$ converter with indirect control (FDC - is fictitious DC interlink with a) three-phase rectified voltage or with b) DC voltage) without filter and protection circuitry

Since the 4QC converter is omitted, the novel scheme of HEV powertrain, Figure 2 makes it possible the parallel operation of ICE and AB using 0×5 $M \times C$ converters. It gives a sophisticated solution making possible as parallel as the autonomous operation of ICE and AB.

Since it deals with parallel operation, such an HEV is series and parallel vehicle. The sizing of paralleling converter (4QC or 0×5 $M \times C$) is then done just for the different power of traction motors and ICE, Figure 4. Practically, the parallel

mode is using during the accelerating and ICE start-up/AB charging regime only.

Structural schemes of AC/AC matrix converters (3×5 $M \times C$, 0×5 $M \times C$) are classical circuitry with three-phase input and five-phase output (3×5 $M \times C$) or DC input and five-phase output (0×5 $M \times C$), respectively. The structural schemes of $M \times C$ converter with indirect control [9, 16-19] used for simulation are shown in Figure 5.

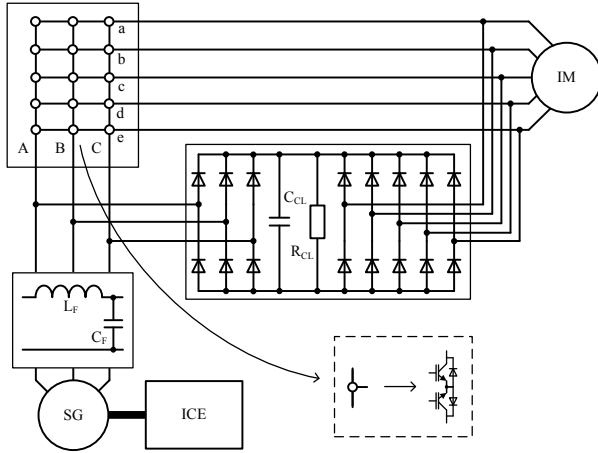


Figure 6 Schematics of MxC propulsion drive with floating clamping protection and input filter

Modeling indirect control we get:

$$[\mathbf{u}_{out}] = \mathbf{T} * [\mathbf{u}_{in}] = \mathbf{I} * \mathbf{R} * [\mathbf{u}_{in}] \quad (1)$$

$$[\mathbf{i}_{in}] = \mathbf{T}^T * [\mathbf{i}_{out}], \quad (2)$$

where \mathbf{T} , \mathbf{I} , \mathbf{R} are transfer matrix of matrix converter, fictitious inverter and rectifier, respectively

$$\mathbf{T} = \begin{bmatrix} S_{RA} & S_{SA} & S_{TA} \\ S_{RB} & S_{SB} & S_{TB} \\ S_{RC} & S_{SC} & S_{TC} \\ S_{RD} & S_{SD} & S_{TD} \\ S_{RE} & S_{SE} & S_{TE} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \\ S_{13} & S_{14} \\ S_{15} & S_{16} \end{bmatrix} * \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} u_A(t) \\ u_B(t) \\ u_C(t) \\ u_D(t) \\ u_E(t) \end{bmatrix} = \begin{bmatrix} m_7(t) & m_8(t) \\ m_9(t) & m_{10}(t) \\ m_{11}(t) & m_{12}(t) \\ m_{13}(t) & m_{14}(t) \\ m_{15}(t) & m_{16}(t) \end{bmatrix} * \begin{bmatrix} m_1(t) & m_3(t) & m_5(t) \\ m_2(t) & m_4(t) & m_6(t) \end{bmatrix} * \begin{bmatrix} u_R(t) \\ u_S(t) \\ u_T(t) \end{bmatrix} = \mathbf{M}_I(t) * \mathbf{M}_R(t) * \begin{bmatrix} u_R(t) \\ u_S(t) \\ u_T(t) \end{bmatrix}, \quad (4)$$

where are modulating matrices with their elements

$$m_{oi}(t) = \frac{t_{oi}}{T_s}, \quad (5)$$

where t_{oi} for output indexes $o \in \langle A, B, C, D, E \rangle$ and input indexes $i \in \langle R, S, T \rangle$

$$[\mathbf{u}_{out}] = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \\ S_{13} & S_{14} \\ S_{15} & S_{16} \end{bmatrix} * \begin{bmatrix} U_{DC+} \\ U_{DC-} \end{bmatrix} = \begin{bmatrix} U_{DC+} \\ U_{DC-} \end{bmatrix} = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} * [\mathbf{u}_{in}] \quad (6)$$

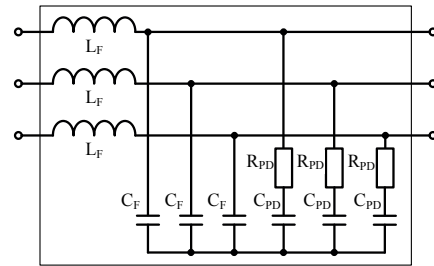


Figure 7 Schematics of the input filter for MxC converter in detail

where U_{DC+} and U_{DC-} is equal $U_{DC}/2$ so, $U_{DC} = U_{DC+} - U_{DC-}$.

Using this approach a space vector PWM can be used for IM control.

3 Clamping protection and filtering circuits

Compulsory parts of the matrix converter mentioned rarely are protection and filtering circuits [5, 20]. Schematics of MxC propulsion drive with floating clamping protection and input filter is shown in Figure 6.

3.1 Designing input LC filter and clamping protection unit

The input filter is very important for MxC especially in the case of the non-harmonic input currents of MxC will be loaded with the synchronous generator by additional distortion power. Design of LC filter should be considered basically from the next points of view [20-21]:

Filter operation at a basic mains frequency of the range 100 - 200 Hz (output frequency of the synchronous generator)

Filter combination behavior in the frequency domain (filter transfer function)

The resonant frequency should be in a range between ten times the line frequency and one-half of the switching frequency, to avoid resonance problems in the lower and upper parts of the harmonic spectrum

Passive damping must be sufficient to avoid oscillation, but losses cannot be so high as to reduce efficiency [5]

Regarding the clamping unit: In generally, energy accumulated in coils is given by their inductances and the appropriate currents flowing through them.

The design procedure for both LC filter (Figure 7) and clamping protection unit has been used by [20].

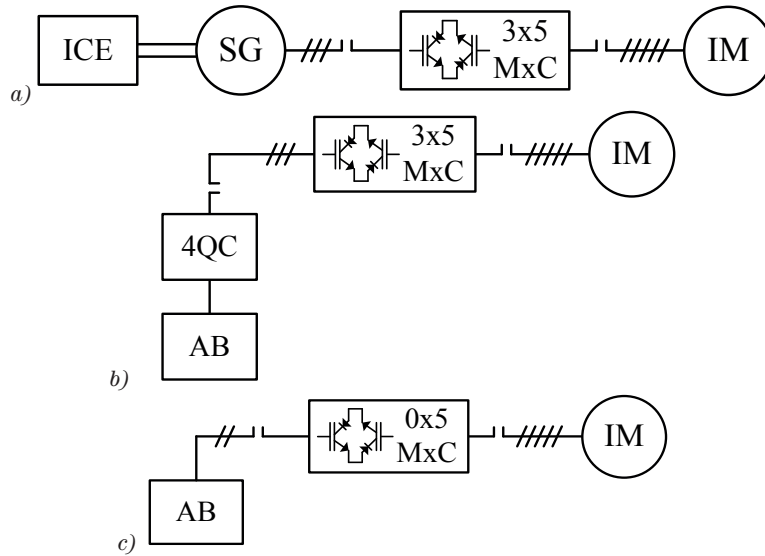


Figure 8 Possible operational model of novel enhanced AC/AC powertrain

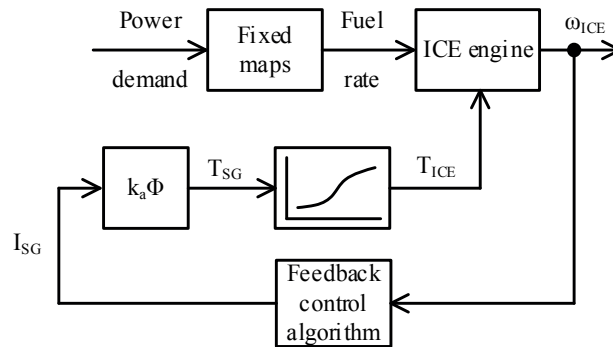


Figure 9 Principle block diagram for ICE engine - PMSG generator control

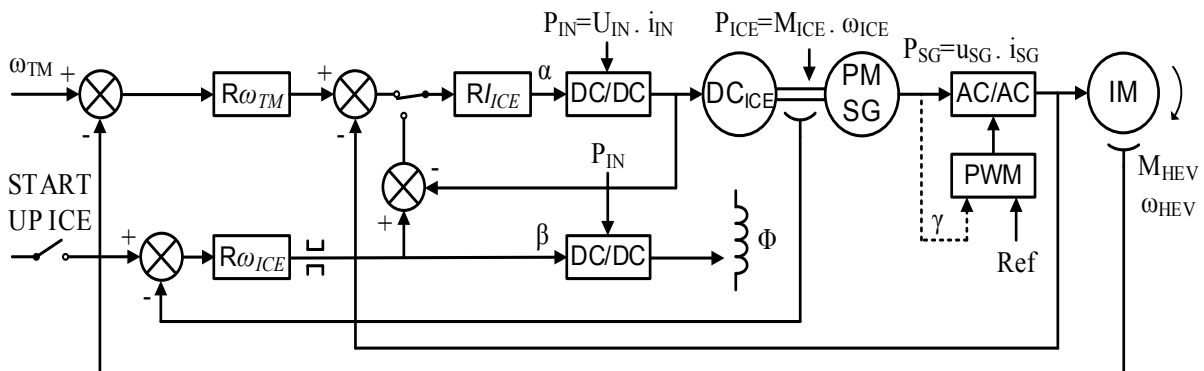


Figure 10 Principle control diagram for ICE engine, PMSG generator, MxC converter and IMs

Designing input LCL filter is needed for 4QC autonomous operation as charging of accu-battery by ICE/SG unit or at starting-up the ICE/SG using accu-battery. To design the filter, some limits on the parameter values should be introduced [22-23]

The capacitor value is limited by the decrease of the power factor at rated power (generally less than 5%). The power factor decrease can also be a function of the ac sensor position as discussed in [22].

The total value of inductance should be less than 0.1 p.u. to limit the ac voltage drop during operation. Otherwise, a higher dc-link voltage will be required to guarantee current controllability, which will result in higher switching losses.

To design the LCL input filter the design procedure using [23] can be used.

Table 1 Parameters of the powertrain

Item	Quantity	Value (dimension)
ICE engine (DC motor, separate exciting)	Output power	30 hp (22 kW)
	Armature voltage	500 V
	Nominal speed	3 000 rpm
	Field voltage	300 Vdc
3 phase PMSG generator	Power	11.5 hp (8.5 kW)
	Nominal torque	27 N.m
	Nominal speed	3 000 rpm
Fictive DC bus voltage	Nominal value	300 Vdc
5 Phase IM induction motor	Output power	7.5 kW
	Output voltage	150 Vrms
	Nominal torque	23 N.m
	Synchronous speed	3 000 rpm
AB accu-battery	Nominal voltage	300 V

Table 2 Parameters of the input filter and floating protection

Input LC filter	Floating protection
$L_f=100 \mu\text{H}$; $C_f=28.2 \mu\text{F}$; $R_{\text{PD}}=0.94 \Omega$; $C_{\text{PD}}=112.8 \mu\text{F}$	$C_{\text{CL}}=1 \text{ mH}$; $R_{\text{CL}}=10 \text{ k}\Omega$

4 Modeling and simulation

Possible operational modes of novel advanced AC/AC powertrain suitable for simulation are shown in Figure 8 a, b, c.

- traction drive/brake: ICE->>SG->>MxC->>5PIM or, respectively 5PIM->>MxC->>SG->>ICE,
- traction drive/brake/charging: AB->>4QC->>MxC->>5PIM or, respectively 5PIM->>MxC->>4QC->>AB,
- traction drive/brake/charging: AB->>MxC->>5PIM or, respectively 5PIM->>MxC->>AB

For simulation purpose, the ICE engine has been substituted by DC separately exciting motor. The main block diagram of a control strategy for ICE engine - SG generator assembly is shown in Figures 9 and 10 [18], created by [24-26].

Algorithm for ICE engine - generator assembly control consisting basically of three steps:

- start-up of ICE engine to reach the idle speed, then
- start-up of traction motor to demanded speed and continuously
- setting-up of the ICE engine to adequate speed and power.

Hybrid operational mode of HEV powering.

Parallel operation of ICE engine and traction accu-battery AB is possible using the novel scheme of HEV powertrain, Figure 4 makes it using 0x5 MxC converters. It gives

a sophisticated solution making possible as parallel as the autonomous operation of ICE and AB. The parameters of the powertrain are as follows given in Tables 1 and 2.

5 Conclusion

Basically, using of [3x5] matrix converter drive with 5-phase motors brings:

- higher efficiency against VSI front-end converter system
- the possibility of independent control of 5-phase motors which is not possible with 3-phase motors.
- battery autonomous traction and a braking regime where 4QC should be completed by [3x5] MxC since auxiliary [0x5] MxC should not be,
- also, charging mode from ICE/SG unit with 4QC needs either control by ICE engine or further DC/DC converter since auxiliary [0x5] MxC not need.

Total comparison and evaluation can be done until when all operation modes of both concepts (with 4QC and with [0x5] MxC) will be simulated and their result known. Both of those concepts make it possible to also combine (parallel) modes of the HEV powertrain.

The article continues in Part II (will be published in Communications - Scientific Letters of the University of Zilina No. 2/2020).

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