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POSSIBLE OPERATION MODES OF HEV VEHICLE WITH DIRECT AC/AC TRANSFER AND 5-PHASE TRACTION MOTORS

The paper deals with operational modes of HEV vehicle with direct AC/AC transfer and five-phase IM traction motors. Such configuration yields smaller voltage drops compared with the serial AC/DC/AC converter and five-phase machines offer some inherent advantages over their three-phase counterparts. Also, dynamical properties of HEV are better due to the absence of a DC link which has accumulating action. Other advantage includes reduced electromagnetic torque pulsation and also noise characteristics of the five-phase drives are better when compared with the three-phase ones. Possible operational modes enable to provide both the single and/or hybrid operations at driving and braking states.

INTRODUCTION

Hybrid electric vehicles (HEV) combine conventional propulsion based on ICE engine with petroleum fuel and electric propulsion with motor powered by accu-batteries or bateries of supercapacitors. Configuration with motor-wheels allows flexibility of the car; it removes the central drive motor and associated transmission parts of the propulsion system of the vehicle. The main advantage of the electric motor in the wheel is adjustable traction and braking torque individually and with high precision without ingestion gearbox, drive shaft, differential gear and other complex and heavy parts of power transmission [1], [9], [10].

There are several modes of operation of driving and braking of hybrid electric vehicle, the single or hybrid ones [1]-[3]:

- pure engine mode: the vehicle is powered with energy provided by electric generator driven by engine; accu-battery does not provide nor takes energy to/from the drive train
- pure electric: ICE is stopped and the vehicle is propelled only by battery energy
- battery charging mode: the engine-generator charges the battery and the traction motors are not supplied
- regenerative braking modes:
  - the engine is turned off, traction motors are operated as generators and the energy provided is used to charge the battery
  - the battery is turned off and the traction motors operate as generators and their energy is used to braking of the ICE engine
  - the engine and battery are turned off and the traction motors operate as generators and the energy is spent by electrodynamic brake in braking resistors
- hybrid modes:
  - the traction power is drawn from both the engine-generator and the battery
  - hybrid battery charging mode: both the engine-generator and the traction motors operate as generators to charge the battery
  - engine traction and battery charging mode: the ICE-generator provides the energy needed for the battery charging and for the vehicle propulsion.

Basically, we can use two different configurations of electrical part of propulsion system: series HEV with AC/DC/AC system [1]-[3] and direct AC/AC system which does not comprise DC interlink and belongs to parallel configurations from the point of view of electrical part configuration. Next text will deal with the later one.

1. DESCRIPTION OF DIRECT AC/AC TRANSFER OF HEV

When omitting systems with mechanical differential, there still remains two different configurations of the direct AC/AC traction systems, Fig. 1. One of them, with electronic differential (Fig. 1a) which needs 2 converters, and the second one, called independent control of machines fed by just one matrix converter (Fig. 1b). But,

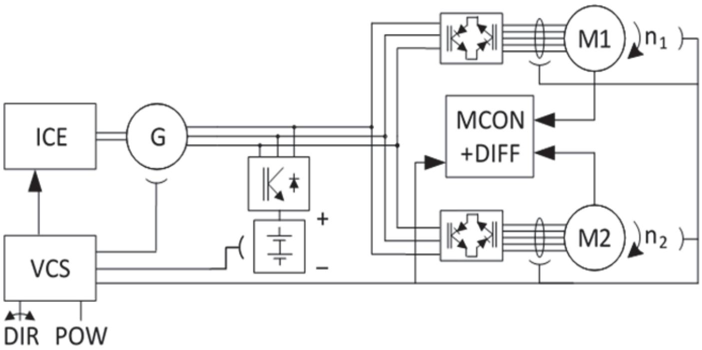

***Fig. 1.** Direct AC-AC propulsion system with two [3*5] matrix converters and electronic differential Fig. 1a, and with one converter and two traction motors connected in parallel, Fig. 1b*

the papers [7]-[9] explain, that, although parallel multi-phase multi-motor drives and series connected multi-phase multi-motor drive systems are feasible and in principle offer good quality of dynamic performance, they do not hold a real prospect for industrial applications so far. Concerning of number of phases of generator and motors, three for [3x5] matrix converters and five for traction motors are usually taken into account [5], [7], so, we do the same.

Traction generator G is suppling two traction motors in back wheels through one (Fig. 1b) or two (Fig. 1a) matrix converters [3x5] MxC. Traction accu-battery AB is connected to the matrix converters either by 3-phase connectin or directly by 2-pole breakers. HEV vehicle is stearing by vehicle control system VCS using inputs DIR (direction) and POW (power).

2. DRIVING (MOTORING) AND BRAKING MODES OF OPERATION - SCHEMATICS

The first part of operation is starting of ICE engine using accu-battery AB, Fig. 2a. Then, it is possible to use one of above mentioned modes given in the Figs. 2b-2f. Some of them may not be used depending on equipment of the HEV vehicle.

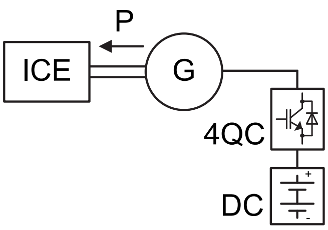

Fig.2a *Start-up of ICE using battery AB*

Motoring of HEV using ICE engine is shown in Fig. 2b. Accu-battery is not operating. Generator G powered by ICE supplies traction motors M1, M2 trough one or two [3x5] matrix converters.

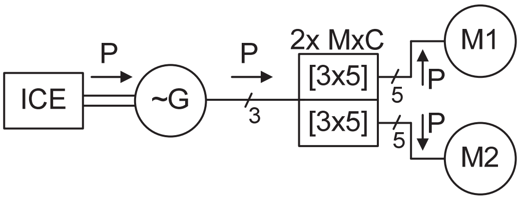

Fig.2b *Motoring: HEV powered by ICE*

Motoring of HEV using Accu-battery AB is shown in Fig. 2c. ICE engine may not be in operation. Accu-battery supplies traction motors M1, M2 trough one or two [3x5] matrix converters.

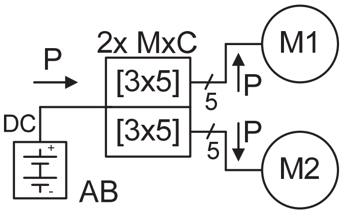

Fig.2c *Motoring: HEV powered by AB*

Braking mode using electro-dynamical brake EDB is presented by schematics in Fig. 2d. Accu-battery AB as well as ICE engine may not be in operation.

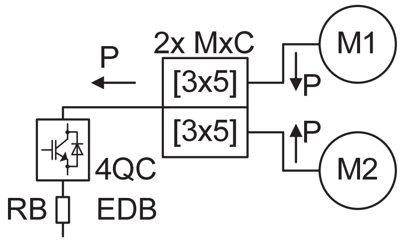

Fig.2d *Braking mode using electro-dynamical brake EDB*

Recuperation braking into accu-battery AB is presented by schematics in Fig. 2e. The engine is turned off, the traction motors are operated as generators and the energy provided is used to charge the accu-battery AB.

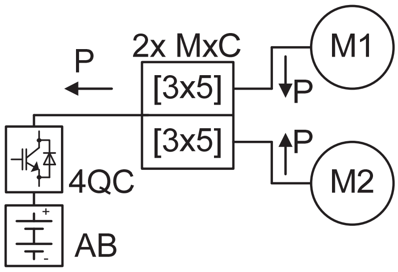

Fig.2e *Braking -recuperation energy into accu-battery AB*

Similarly as above, there is battery charging mode, Fig. 2f: The engine – generator charges the battery and the traction motors are not supplied.

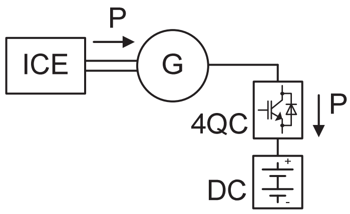

Fig. 2f *Battery charging mode using engine – generator*

In principle, there are three hybrid modes of HEV vehicle: motoring and braking, Fig. 2g.

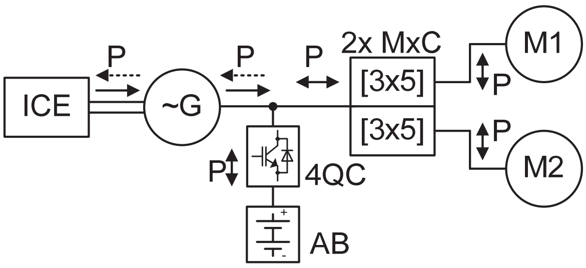

Fig.2g *Hybrid modes: motoring and/or braking of HEV*

These modes are:

- Motoring mode: the traction power is drawn from both the engine-generator and the batteries.
- Engine traction and battery charging mode: The ICE-generator provides the energy needed for the batteries charging and the propulsion vehicle.
- Hybrid batteries charging mode: both the engine-generator and the traction motor operate as generator to charge the batteries.

3. MODELLING AND SIMULATION OF CHOSEN OPERATIONAL MODES

3.1. Modelling of [3x5] matrix converter and 5Φ traction motor

The MxC can be studied based on two separated virtual stages reflecting the two stages of the conventional converter (rectifier - inverter) [10], [11, [12], Fig. 3. Since at any given time at least one phase of the power supply voltage is positive and at least another phase is negative, the fictitious DC link voltage is given by difference between U^+ and U^- potentials.

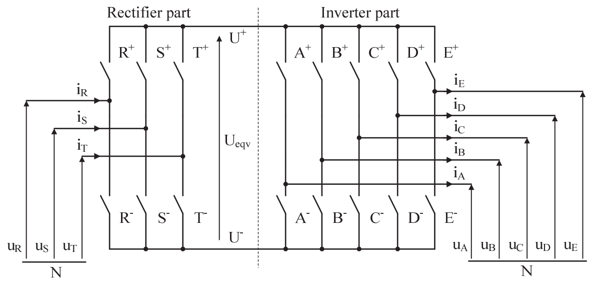

Fig. 3 *Virtual model of indirect MxC with fictitious DC link*

Then, MxC output voltage can be calculated by the equations

$$\begin{bmatrix} u_a \\ u_b \\ u_c \\ u_d \\ u_e \end{bmatrix} = \begin{bmatrix} u_{m1} & 1-u_{m1} \\ u_{m2} & 1-u_{m2} \\ u_{m3} & 1-u_{m3} \\ u_{m4} & 1-u_{m4} \\ u_{m5} & 1-u_{m5} \end{bmatrix} \begin{bmatrix} R^+ & S^+ & T^+ \\ R^- & S^- & T^- \end{bmatrix} \begin{bmatrix} u_R \\ u_S \\ u_T \end{bmatrix} \qquad (1)$$

where $u_{mk} = r\cos(\varphi)\left(\omega_0 t - \frac{2\pi}{5}(k-1)\right) + 1/2$

for $k = 1 \dots 5$

$r = \frac{\cos(\varphi-\pi/3)}{\cos(\varphi)}$ and $\varphi = |\omega t|_{\mathrm{mod}(\frac{\pi}{3})} - \pi/6$

$R^+ \dots T^-$ are logical variables for the *max* and *min* input phase voltage.

Based on above equation the fictitious DC interlink can be calculated, and used for 5Φ traction motor modelling. Stator quantities of the motor can be expressed using *α-β* Clarke transformation system as

$$\boldsymbol{x}_s = \frac{2}{5}\left(x_a + x_b e^{j\frac{2\pi}{5}} + x_c e^{j\frac{4\pi}{5}} + x_d e^{j\frac{6\pi}{5}} + x_e e^{j\frac{2\pi}{5}}\right) \qquad (2)$$

Then

$$\boldsymbol{u}_s = \mathrm{Re}(\boldsymbol{u}_s) + j\mathrm{Im}(\boldsymbol{u}_s) = u_\alpha + ju_\beta \qquad (2a)$$

and

$$\boldsymbol{i}_s = Re(\boldsymbol{i}_s) + jIm(\boldsymbol{i}_s) = i_\alpha + ji_\beta \qquad (2b)$$

where vector of stator (also rotor) current can be obtained from dynamic model of the motor

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} \boldsymbol{i}_s \\ \boldsymbol{i}_r \\ \omega_m \end{pmatrix} = \boldsymbol{A}\begin{pmatrix} \boldsymbol{i}_s \\ \boldsymbol{i}_r \\ \omega_m \end{pmatrix} + \boldsymbol{B}\begin{pmatrix} \boldsymbol{u}_s \\ 0 \\ 0 \end{pmatrix}, \qquad (3)$$

where $\boldsymbol{A}$ a $\boldsymbol{B}$ are matrices of parameter of the system.
and torque eguation

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

3.2. Simulation experiment results

The simulation has been accomplished in Matlab-Simulink environment. Both, motoring and braking modes during start-up and at steady state are presented thereinafter.

There is in the Fig. 4a and 4c simulation result of motoring of HEV when traction system is powered by ICE engine.

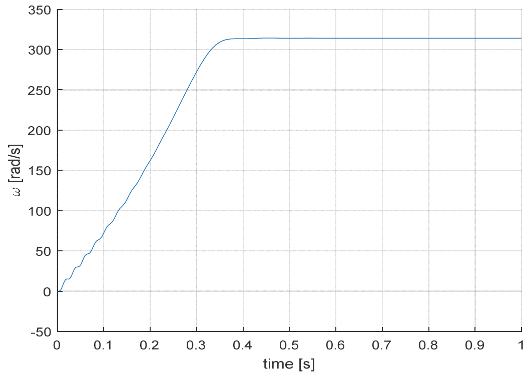

Fig. 4a *Motoring: HEV powered by ICE – start up: ω_m*

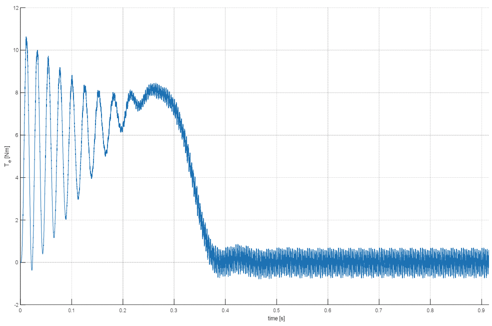

Fig. 4b *Motoring: HEV powered by ICE – start up: T_e*

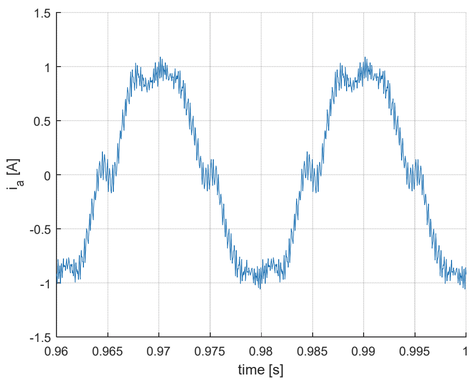

Fig. 4c *Motoring: HEV powered by ICE – phase current at steady state*

Simulation results of braking mode using electro-dynamical brake are presented by the graphs in Fig. 4c. As mentioned above, the accu-battery as well as ICE engine may not be in operation.

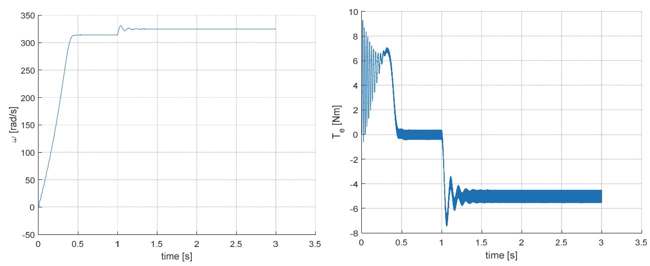

Fig. 4c *Braking mode using electro-dynamical brake - ω_m and T_e*

Simulation result of recuperation braking energy into accu-battery is presented by the grafics in Fig. 4d. The engine is turned off.

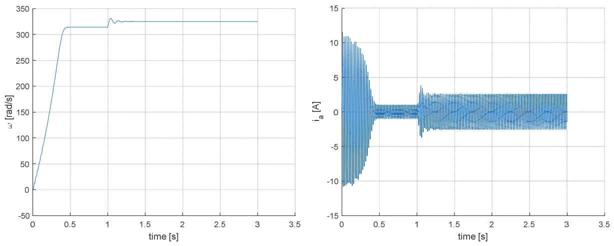

Fig. 4d *Recuperation of braking energy into accu-battery -* ω_m *and* i_a

CONCLUSION

The possible operational modes of direct AC/AC transfer with [3x5] MxC and five-phase IM traction motors have been presented by means of simulation experiments. They showed good operation at the drivin (motoring) and braking actions. Major advantages of using such AC/AC power transfer with [3x5] MxC and five-phase IM traction motors have been mentioned as their higher torque density, smaller voltage drops, greater efficiency, better fault tolerance and better noise characteristics. Hybrid modes simulation is rather complex, and it will be, consequently, investigated in the next contributions of the authors.

ACKNOWLEDGEMENT

The reported study was supported from Slovak Grant Agency VEGA by the grant No. 1/0928/15. Author also thank to the R&D operational program Modernization of Research Infrastructure in the Field of Electrotechnics, Electrotechnical Materials and Information-Communication Technologies, ITMS 26210120021 funded by the European regional development fund (ERDF).

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