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CONTROL OF HYBRID AND ELECTRICAL VEHICLE WITH FIVE-PHASE AC MOTOR

The paper deals with control of series HEV hybrid- and BEV electric vehicles including electronic differential and five-phase traction induction electrical motors. Possibilities of dynamical and directional servo control are greater because of five-phase machines offer some inherent advantages over their three-phase counterpart. Major advantages of using a five-phase machine instead of three-phase ones consists in their higher torque density, greater efficiency, and fault tolerance. Other advantage includes reduced electromagnetic torque pulsation, and reduction in the required rating per inverter leg. Noise characteristics of the five-phase drives are better when compared with the three-phase ones.

INTRODUCTION

With the increasing number of cars entered circulation annually takes place and increases fuel consumption, increased pollution due to emissions from internal combustion engines (ICE), which is used for propulsion. Automobile propulsion system needs to develop maximum torque at zero speed. This cannot be achieved with conventional ICE engines [4]. For ICE vehicles is efficiency rather small at low speeds and has a maximum value near rated speed. The usual arrangement of the electrical also non-electrical vehicles involves only one traction engine driving two wheels using a differential gear. In contrast, HEV and EV vehicle with multiple motor-wheels may represent benefits such as improving vehicle performance with better weight distribution and no power failure in the differential and the possibility to control the acceleration of each wheel separately for better stability in difficult or dangerous situations. Furthermore, this configuration provides full controllability of torque applied to each wheel of the engine and increased regenerative braking capability.

Manufacturers of on- and off-road industrial vehicles are competing around the world to bring higher value products to the market. The challenges are big and the pace if innovation is accelerating. The main drivers behind the development are still traditional values, e.g. usability, productivity, uptime, safety and total cost ownership. One area in particular is the technology awareness of manufacturers and system providers are learning in their everyday life which is pushing the needs for customizable instrumentation, connectivity and option based machine configuration

Configuration with motor-wheels allows flexibility of the car; 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].

1. HEV WITH ELECTRONIC DIFFERENCIAL AND MOTOR WHEELS

Hybrid electrical vehicles

There are several configurations of electric and hybrid vehicles [2], [8]: Electric vehicles equipped with electric batteries and/or supercapacitors called Battery Electric Vehicles; hybrid electric vehicles which combine conventional propulsion based on ICE engine with petroleum fuel and electric propulsion with motor powered by batteries or supercapacitors called Hybrid Electric Vehicles; Electric vehicles equipped with fuel cells, called Fuel Cell Electric Vehicles).

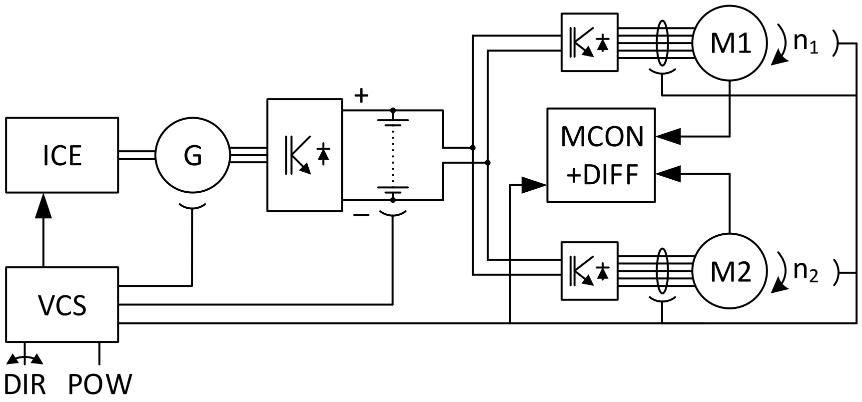

Fig. 1. Series HEV with electronic differential and motor wheels.

Concept of hybrid electric vehicle with ICE-electric motor aims to overcome the disadvantages of the pure electric vehicles, whose engines are powered by electric batteries: the limited duration of use (low autonomy) and time recharging for batteries. There is, in Fig. 1., shown solution of the series HEV with electronic differential and motor wheels.

2. HEV WITH ELECTRONIC DIFFERENCIAL AND FIVE-PHASE IM MOTOR

The possible operating modes of series hybrid electric drive trains are by Ehsani, 2005, [9]: Pure electric: ICE is stopped and the vehicle is propelled only by batteries energy; Pure engine mode: the vehicle is powered with energy provided by electric generator driven by engine. The batteries no provide and do not take energy from the drive train; Hybrid 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; Regenerative braking mode: the engine is turned off and the traction motor is operated as generator and the energy provided is used to charge the batteries; Batteries charging mode: The engine – generator charges the batteries and the traction motor is not supplied; Hybrid batteries charging mode: both the engine-generator and the traction motor operate as generator to charge the batteries.

Traction drive used in electric vehicles can be divided into two categories: single-drive system and multi-drive systems. With multi-drive systems, the motor controllers must additionally be configured to provide an electronic differential effect i.e. they must also perform a similar function as their mechanical differential counterpart. Thus, the electronic differential must take account of the speed difference between the two wheels when cornering.

The proposed traction system consists of two AC mostly synchronous machines that ensure the drive of the two back-driving wheels. Such systems are known as multi-machine multi-converter systems (MMS) [1] and are recognized via the coupling system type: either an electric nature, or a magnetic and/or mechanical coupling used in several electric machines propelling the vehicle. The proposed control structure [2], called *independent machines for speed control*, is an electronic differential method based on direct torque fuzzy control. One of possible solution based on mentioned principle is shown in Fig. 2 below. Detailed description of control system for electronic differential is given in the work Hartani et al., [10].

Using traction five-phase AC motor

Recently, more and more often there appears papers dealing with five-phase induction motor drives. Variable speed electric drives predominately utilize the three-phase machines. However, since the variable speed AC drives require a power electronic supply, the number of machine phases is essentially not limited. This has led to increase for interest in five-phase AC drive applications. The five-phase machines offer some inherent advantages over their three-phase counterpart, [5].

Major advantages of using a five-phase machine instead of three-phase ones consists in their higher torque density, greater efficiency, and fault tolerance. Other advantage includes reduced electromagnetic torque pulsation, and reduction in the required rating per inverter leg. Noise characteristics of the five-phase drives are better when compared with the three-phase ones, [3], [4], [14].

3. PERFORMANCE OF FIVE-PHASE AC MOTOR

Definition equations

The basic circuit scheme of five-leg VSI inverter with five-phase IM motor is given in Fig. 5 (bottom). Stator quantities of the motor can be expressed using $\alpha\beta$ Clarke transformation system as

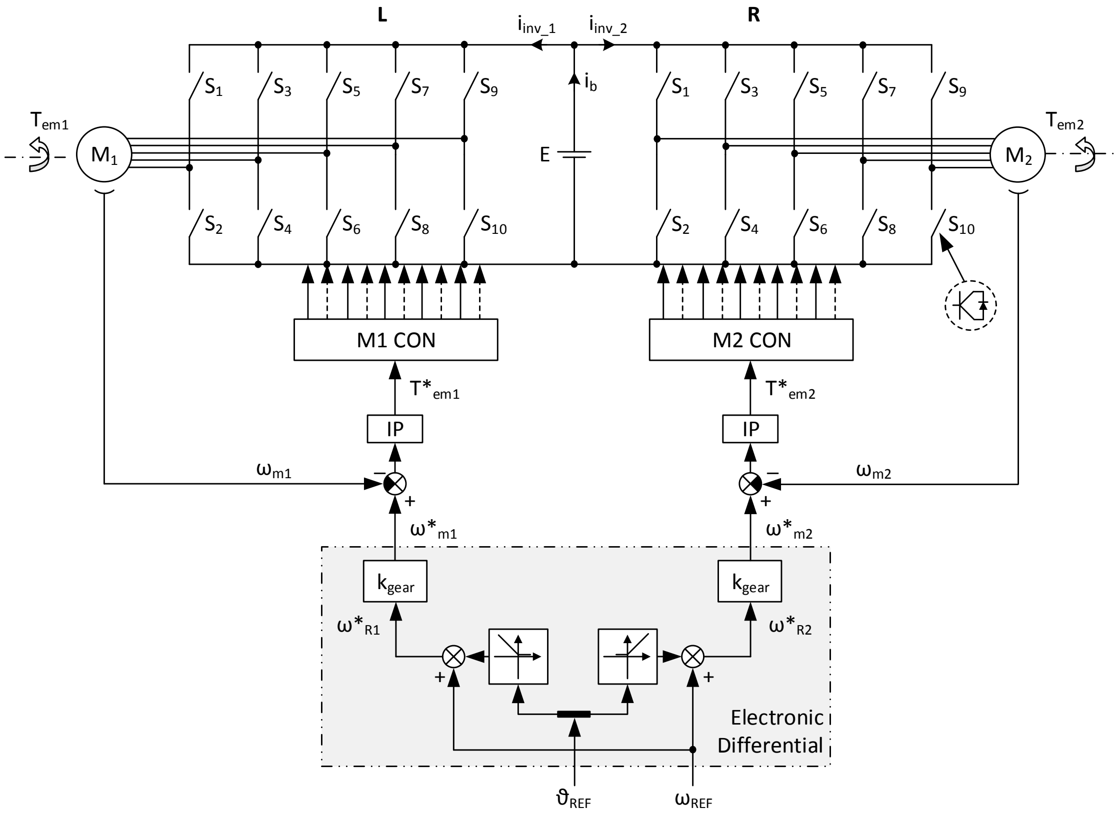

Fig. 2. Electronic differential control system for five-phase IM motor.

$$\boldsymbol{x}_s = \frac{2}{5}\left(x_a + x_b e^{j\frac{2\pi}{5}} + x_c e^{j\frac{4\pi}{5}} + x_d e^{j\frac{6\pi}{5}} + x_e e^{j\frac{2\pi}{5}}\right). \qquad (1)$$

Thus

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

and

$$\boldsymbol{i}_s = Re(\boldsymbol{i}_s) + jIm(\boldsymbol{i}_s) = i_\alpha + ji_\beta \qquad (3)$$

where vector of stator current is possible to obtain from dynamic model of the motor

$$\frac{d}{dt}\begin{pmatrix}\boldsymbol{i}_s\\ \boldsymbol{i}_r\\ \omega_m\end{pmatrix} = \boldsymbol{A}\begin{pmatrix}\boldsymbol{i}_s\\ \boldsymbol{i}_r\\ \omega_m\end{pmatrix} + \boldsymbol{B}\begin{pmatrix}\boldsymbol{u}_s\\ \boldsymbol{u}_r\\ 0\end{pmatrix}, \qquad (4)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \frac{T_{elmg} - T_{load}}{J_m}. \qquad (5)$$

Where $\boldsymbol{i}_r$, in case of synchronous PM motor is equal 0.

Simulation experiment results

Modelling and simulations were done in Matlab/Simulink programming environment. Simulation results can be seen in Fig. 4-6 and Fig.

Time waveforms of i_α, i_β stator currents using $\alpha\beta$ Clarke transformation system at steady-state condition are shown in Fig. 4.

Since the stator current, as it can be seen, is nearly sinusoidal waveforms, the stator voltages are strongly non-harmonic and pure impulse waveforms.

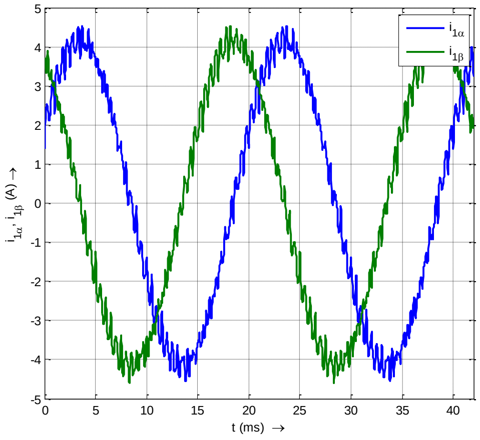

Fig. 3. *Stator current i_α, i_β in $\alpha\beta$ Clarke system of the AC IM motor*

Since the stator current, as it can be seen, is nearly sinusoidal waveforms, the stator voltages are strongly non-harmonic and pure impulse waveforms.

Time waveforms of u_α, u_β stator currents using $\alpha\beta$ Clarke transformation system at steady-state condition are shown in Fig. 6 and 7.

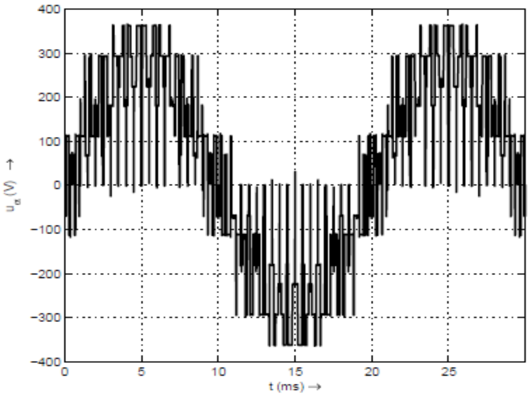

Fig. 6 *Stator voltage u_α of the FPIM motor*

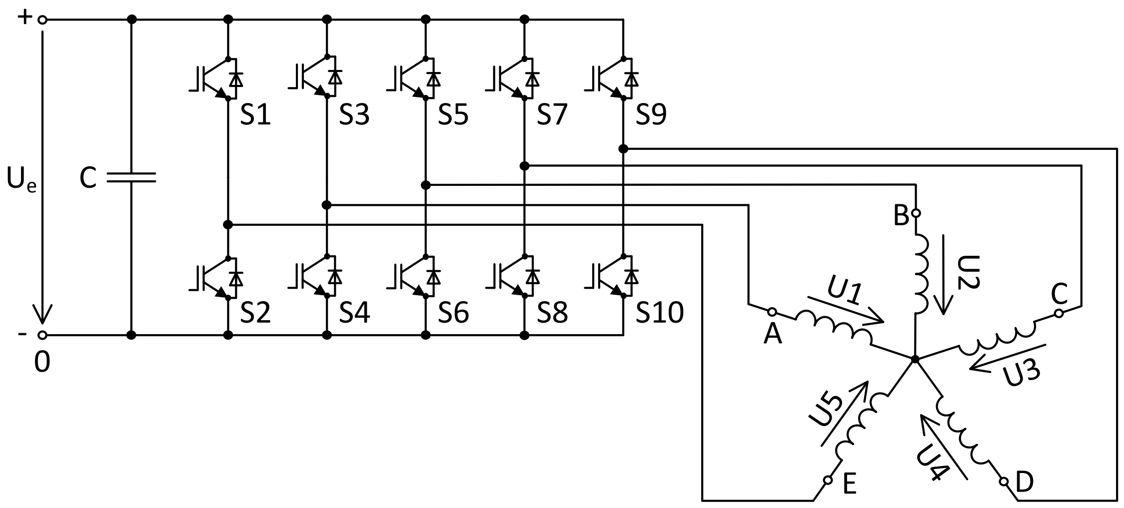

Fig. 5. Circuit scheme of five-leg VSI inverter with five-phase IM motor

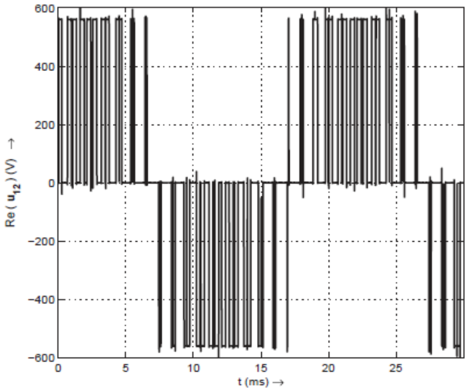

Fig. 7. *Stator voltage u_α of the FPIM motor*

A fault tolerance property of FPIM is evident in Fig. 8 under one phase and *T_load* = *T_nom*.

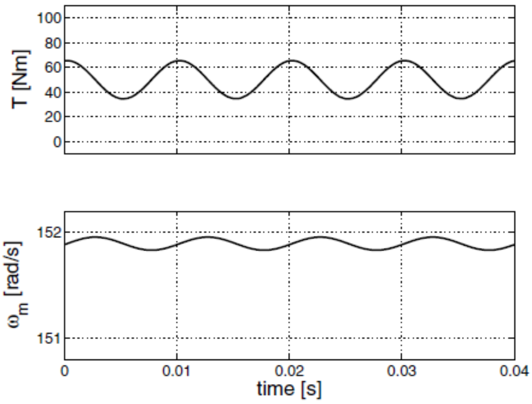

Fig. 8. *Torque and speed ripple of five-phase machine with open one phase and $T_{load} = T_{nom}$*

In spite higher torque and speed ripple the average value of torque is still about 80 % of nominal one.

CONCLUSION

The paper shows possibility of dynamical- and directional servo control of series HEV hybrid- and BEV electric vehicles using/including electronic differential and five-phase traction AC electrical motors.

Advantages of using of the five-phase traction induction electrical motors are assumed as: Little torque ripple, higher torque density, greater efficiency, and fault tolerance. Other advantage includes reduced electromagnetic torque pulsation, and reduction in the required rating per inverter leg. Simulation results have shown good performance of five-phase AC IM motor: the stator current, as it can be seen from Fig. 3, is nearly sinusoidal waveforms, the torque and speed ripple under one phase fault acceptable for such a vehicle operation.

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Kontrola pojazdów hybrydowych i elektrycznych z pięciofazowym silnikiem trójfazowym

W artykule omówiono sterowanie pojazdami elektrycznymi hybrydowymi i HEV typu HEV, w tym elektronicznymi i pięciofazowymi silnikami indukcyjnymi trakcyjnymi. Możliwości dynamicznego i kierunkowego sterowania serwomechanizmem są większe dzięki maszynom pięciofazowym oferującym pewne zalety związane z ich odpowiednikiem trójfazowym. Główne zalety używania maszyny pięciofazowej zamiast trójfazowej polega na ich wyższej gęstości momentu obrotowego, większej wydajności i odporności na uszkodzenia. Inną zaletą jest zmniejszenie pulsacji momentu elektromagnetycznego i zmniejszenie wymaganej wartości znamionowej na stopę falownika. Charakterystyka hałasu napędów pięciodniowych jest lepsza w porównaniu z silnikami trójfazowymi.

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