Integrated DC Electrical Machine for All-Electric
and Hybrid-Electric Vehicles

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Abstract. In the paper a concept and physical and mathematical models of the integrated DC electrical machine for automotive vehicles with the electromechanical or hybrid-electromechanical drive is presented. The DC electrical machine under consideration is a double DC-AC/AC-DC commutator synchronous motor/generator with electronic commutators and an electromagnetic exciter on a common shaft. The paper contains a short description of the mechatronic control system of this DC electrical machine, operating both as an electromechanical motor and/or a mechanoelectrical generator. Besides, the oscillograms from the laboratory tests of this electrical machine are also presented. The analysis of the operation of this DC electrical machine is facilitated by the physical and mathematical models presented in the paper. Thanks to the use of an innovative electronic AC-DC commutator, operating as a transistor AC-DC rectifier, the energy efficiency and reliability of this electrical machine was improved during operation as a mechanoelectrical generator.

1. Introduction

In recent years, it has been noted that numerous research and development (R&D) works have been undertaken to develop a DC motor integrated electromechanical drive (IEMD) for modern automotive vehicles, which would eliminate the conventionally used internal combustion engines (ICEs) [1].

During the operation of the DC motor, as a DC-AC/AC-DC commutator synchronous motor with electronic commutators and electromagnetic exciter, there is an easy possibility of speed and torque control, while during operation as a mechanoelectrical generator it is possible to convert mechanical energy and deliver it to the on-board DC network during recuperative braking [2].

2. The double DC electrical machine with the electronic commutators and electromagnetic exciter

Until now, there are no known in modern literature or practically used constructions of an integrated DC-AC/AC-DC commutator synchronous motor/generator based on a double DC electrical machine with electronic commutators and electromagnetic exciter on a common shaft, despite the fact that the use of such an electrical machine makes it possible to adjust the magnetic flux of its inductor [3].

This is a valuable advantage, both during operation, as a mechanoelectrical generator (convenient adjustment of the output voltage by changing the excitation current), and - acting as an electro-
mechanical motor (wider range of rotational speed control, not only by adjusting the armature current but also by attenuating the inductor magnetic flux as in the case of an off-load DC commutator motor with a mechanical split-ring/flat commutator) [4].

The authors of this article would like to present an alternative design solution of an integrated DC-AC/AC-DC commutator synchronous motor/generator based on a double DC electrical machine with electronic commutators and electromagnetic exciter on a common shaft, for all-electric and hybrid electric vehicles (see Figures 1, 2 and 3).

In order to carry out experimental tests of a new integrated DC-AC/AC-DC commutator synchronous motor/generator with electronic commutators and electromagnetic exciter on a common shaft, a double AC electrical machine with a rotating AC-DC rectifier and electromagnetic exciter, type E1X13S A / 2, 8 kVA / 400 V from LINZ Electric (Fig 1b), equipping it with two additional electronic commutators together with their microcontroller [5], was used.

The above-mentioned double AC electrical machine is used as an AC mechanoelectrical generator when operating at constant speed and has not been used as a DC-AC/AC-DC commutator synchronous motor/generator with electronic commutators and electromagnetic exciter on a common shaft. This double AC electric machine has electromagnetic exciter built into the shaft, equipped with an electronic commutator, acting as a rotating AC-DC rectifier. After making the necessary switching configurations of the winding of the armature of the double AC electrical machine, its operation as a mechanoelectrical generator did not cause any difficulties. However, one of the serious problems to be solved was the development of a universal electronic commutator of the electromagnetic exciter to ensure proper control of the integrated DC-AC/AC-DC commutator synchronous motor/generator.

In order for a double AC electric machine to operate as a DC-AC/AC-DC commutator synchronous motor/generator with electronic commutators and electromagnetic exciter on a common shaft, a triangular or sinusoidal variable magnetic flux should be created in the electromagnetic exciter, which causes the alternating current to be induced in its armature, also when the shaft of a double AC electrical machine is stationary. The creation of a suitable magnetic flux of excitation in the inductor of the main electrical machine will become possible after the alternating current is straightened out. This is a pre-requisite for creating an electromagnetic torque on the shaft of this double electric machine (figure 2).
Figure 2. Waveforms of the voltage and current of the electromagnetic exciter’s inductor of a DC-AC/DC-DC commutator synchronous motor/generator during operation as an electromechanical motor as well as a mechanoelectrical generator and its control circuit [4].

For this purpose, an electronic commutator of the electromagnetic exciter along with its 8-bit microcontroller in the mechatronic control system was developed. The electronic commutator of the electromagnetic exciter, acting as an DC-DC/DC-AC converter is composed of four electric valves in a single-phase commutation matrixer, realized on MOSFETs, with a relatively low resistance in the conduction state, thanks to which high energy efficiency of the electronic commutator is possible. The electronic commutator of the main armature of an DC-AC/AC-DC commutator synchronous generator with electromagnetic excitation was realized on an integrated module of six MOSFETs in a single housing, using a new generation of this type of modules, type M600-Mitsubishi FM600 (figure 3). Figure 3 shows the DC-AC/AC-DC commutator’s mounting plate, based on IR2136 integrated circuit, which is installed on a connector box of the MOSFET module, located in the terminal box of the DC-AC commutator synchronous motor.
The DC-AC/AC-DC commutator plate is designed with the assumption that its output terminals are at the same time the connector (plugs) of the MOSFET module. This allows to avoid additional wired connections between the mounting plate and the MOSFET module’s commutator. In this way the resistance, inductance, and capacitance parasitic values are reduced; and a more compact design of the modified DC-AC/AC-DC commutator of the double AC electrical machine is achieved.

2.1. The physical model of an integrated AC-DC commutator synchronous generator with electronic commutators

The integrated AC-DC commutator synchronous generator (figure 5) is equipped with three electronic commutators: the static AC-DC commutator of an electromagnetic exciter (using four K7- K10 electrical valves), the rotating AC-DC commutator of main electrical machine, realized on diodes D1-D6, feeding the winding of an \( L_f \) inductor, and the static main armature DC-AC/AC-DC electronic commutator, realized on six K1-K6 electric valves and bypassing these electrical valves - diodes.
Figure 5. Physical model of an integrated DC-AC/AC-DC commutator synchronous motor/generator with three electronic commutators and electromagnetic exciter [4]

2.2. The use of electronic commutator, acting as a transistor rectifier

The silicon diode, commonly used as a structural component of conventional diode AC-DC rectifiers, has the basic disadvantage of a relatively high voltage drop in the current conduction mode.

Figure 6 shows that in the range of 2 - 10 A forward current, the forward voltage drop across a single MOSFET used for the FM600 TU-3A module ($R_{DS\,(ON)} = 1.5 \text{ mΩ}$) is within the range 0.003 - 0.015 V, while the forward voltage on the power diode is in the range 0.7 - 0.8 V.

An advantage of replacing semiconductor power diodes by the MOSFETs is obvious, especially in the range of smaller currents - voltage drops on the electrical valve are reduced many times (figure 6), for example, for a direct current of 50 A - about 10 times, which it is connected with the same scale of changes in the decrease of power losses on heat in electrical valves.

Limiting the heat loss in the electrical valves is associated not only with the improvement of the energy efficiency ratio of the AC-DC rectifier, but also with the reduction of its dimensions and costs of heat sinks, and the improvement of its reliability, resulting from the lowering of the operating temperature of the electrical valves.
3. Synthetic mathematical model of the DC-AC commutator synchronous motor with electronic commutators

Synthetic mathematical model of the DC-AC/AC-DC commutator synchronous motor/generator with electronic commutators in dynamical systems approach and matrix notation has the form of the Euler-Lagrange II order differential equation of the dynamics [4]-[7]:

$$\begin{bmatrix} \frac{d}{dt} \left( \frac{\partial T^*}{\partial \{q\}} \right) - \frac{\partial T^*}{\partial \{q\}} + \frac{d}{dt} \left( \frac{\partial T_F^*}{\partial \{q\}} \right) - \{Q\}^T \end{bmatrix} \delta \{q\} = 0$$  \hspace{1cm} (1)

where:
- $T^*$ - kinetic conservative energy of any mechatronic dynamical hypersystem;
- $V$ - potential conservation energy of any mechatronic dynamical hypersystem;
- $T_F^*$ - non-conservation kinetic energy of any mechatronic dynamical hypersystem;
- $\{q\}$ - a vector of independent generalized coordinates of any mechatronic dynamical hypersystem;
- $\{q\} = \frac{d}{dt} \{q\}$ - derivative of a vector of independent generalized coordinates of any mechatronic dynamical hypersystem;
- $\{Q\}$ - a vector of the extortion forces of generalized non-conservative, of any mechatronic dynamical hypersystem.

In the above Euler Lagrange II order differential equation of dynamics in the dynamical systems approach one can use the matrix record of coordinates and generalized velocities and scalar functions of conservative kinetic $T^*$ and potential conservation energy $V$, as quadratic forms, partial derivatives of supersaturated coordinates matrices.

Thus, the mathematical model of a multifunctional commutator synchronous direct current motor with electronic commutators can be written with a differential equation in a matrix notation in the form:
The reference text is too complex and contains advanced mathematical notation. It seems to be discussing the operation and design of electric machines, specifically focusing on synchronous motors and generators with AC-DC commutators. The text appears to be using derivatives and matrix notation to describe the dynamics of these systems, which is typical in electrical engineering literature.

**Conclusions**

Due to the fact that the integrated AC-DC commutator synchronous generator has an electromagnetic excitation, in comparison with existing electrical machines with magneto-electric excitation (with permanent magnets) allows a greater range of speed control during operation as a DC-AC commutator synchronous motor. In addition, thanks to the use of an AC-DC commutator in the form of a transistor, a much higher energy efficiency can be obtained compared to the efficiency of a conventional diode AC-DC rectifier, since voltage drops at the electrical valves under load proved to be very small.

A double AC electric machine with electromagnetic excitation, equipped with appropriate DC-AC and AC-DC commutators, can act as a DC-AC/AC-DC commutator synchronous motor/generator in civil and military all-electric and hybrid-electric vehicles.

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