High-Performance AC-DC Power Electronic Converter Generator for Hybrid-Solar Vehicles

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Abstract: This paper describes the principles of operation and the physical model of an advanced AC-DC converter generator (with the electronic converter acting as an AC-DC rectifier with reverse-conducting MOSFETs (metal-oxide semiconductor field-effect transistors) as fast-electronic switches with a relatively low ON-state voltage drop) for HSVs. An AC-DC converter, when seen as an AC-DC rectifier, can be used in many fields, e.g., for multi-functional AC-DC/DC-AC converter generator/starter and conventional DC-AC converter motors and AC-DC converter generators or generator sets, welding machines, etc. The paper also describes a novel AC-DC converter, with reverse-conducting transistors and without the use of optoelectronic separation (which does not require a separate power supply), which may be easily realized in IC (integrated-circuit) technology. Computer simulation allows for waveform evaluation for timing analysis of all components of the AC-DC-converter’s physical model, both during normal operation as well as in some states of emergency. The paper also presents the results of bench experimental studies where the MOSFETs were used as fast-electronic switches with a relatively low ON-state voltage drop. For experimental studies, a novel AC-DC converter has been put together on the Mitsubishi FM600TU-3A module. The AC-DC converter with reverse-conducting transistors in a double-way connection has a lot of advantages compared to the conventional AC-DC converter acting as a diode rectifier, such as higher energy efficiency and greater reliability resulting from the lower temperature of electronic switches.

Key words: HSV (hybrid-solar vehicles), electronic switches, electronic converter, power losses.

1. Introduction

HSV (hybrid solar vehicles) could combine the advantages of HEV (hybrid-electric vehicles) and SE (solar energy), by the integration of PhPs (photovoltaic panels) in a HEV. But it would be simplistic to consider the development of a HSV as a straightforward addition of PhPs to an existing HEV, which could be considered just a first step. To maximize the benefits coming from the integration of PhPs with HEV technology, it is required to perform an accurate re-design and optimization of the whole vehicle-powertrain system [1, 2].

In these vehicles, in fact, there are many mutual inter-actions between energy flows, propulsion system component sizing, vehicle dimension, performance, mass and size as well as costs, and the interaction between these factors is much more critical than in HEVs or CAV (conventional automotive vehicles) [3-6]. Particularly, the presence of PhPs requires to study and develop specific solutions, since instead of the usual “charge sustaining” strategies adopted in HEV, proper “charge depletion” strategies have to be adopted, to account for the Ch-E/E-Ch (chemo-electrical/electro-chemical) storage battery recharging during parking [7, 8]. Moreover, advanced look-ahead capabilities are required for HSVs. In fact, at the end of driving the final SOC (state of charge) is required to be low enough to allow full storage of solar energy captured in the next parking phase,
whereas, the adoption of an unnecessary constantly low value of final SOC would give additional energy losses and compromise Ch-E/E-Ch storage battery life-time. The optimal management of Ch-E/E-Ch storage battery would therefore require a previous knowledge of the SE to be captured in next parking phase that can be achieved through real-time access to weather forecast [9-12]. The impact of PhPs can be significantly improved by adopting suitable MPPT (maximum power point tracking) techniques, whose role is more critical here than in fixed plants. The recourse to an automatic sun-tracking roof to maximize captured energy in parking phases has also been studied [13-15].

Moreover, as it happens for other HEVs working in start-stop operation, an optimal power split between the ICE (internal combustion engine) and Ch-E/E-Ch storage battery pack must be pursued while also taking into account the effect of ICE thermal transients. Previous studies conducted by the research group on series HSVs demonstrated that the combined effects of ICE, AC-DC converter generator and Ch-E/E-Ch storage battery losses, along with cranking energy and thermal transients, produce non trivial solutions for the ICE/generator group, which does not necessarily operate at its maximum efficiency. The strategy has been assessed via optimisation done with GA (genetic algorithms), and implemented in a real-time rule-based mechatronic control strategy [16-18].

The objective of this paper is to present an advanced AC-DC converter generator for HSVs (with the reverse-conducting MOSFETs (metal-oxide semiconductor field-effect transistors) electronic converter acting as the AC-DC rectifier).

Experimental results confirm a significant increase in the efficiency of the advanced on-board AC-DC converter generator due to a low ON-state voltage drop across the novel AC-DC converter’s reverse-conducting MOSFETs in comparison with a high ON-state voltage drop across the conventional AC-DC converter’s power diodes. It is also valid that in this case, the advanced AC-DC converter generator starts to operate at low ICE rotational-speed values, which is especially important for improving the on-board power-supply quality and overall efficiency, especially when a HSV’s ICE is running slowly in neutral gear [19].

In this paper, the authors examined a novel AC-DC commutator acting as an AC-DC rectifier in the three-phase double-way connection, comprising of two heteropolar (anode and cathode) commutating groups of electronic switches. In this novel AC-DC converter, the power field-effect transistors have replaced the power diodes. The silicon power diode, which is widely used as a component of the conventional diode rectifier, has a fundamental disadvantage, namely a relatively high forward-voltage drop to minimise power losses (voltage drops) on the AC-DC converter’s switches (Fig. 1).

Among other things, in the conventional AC-DC converter generators with electronic converters (i.e., alternators with diode rectifiers), a rectification of the three-phase armature currents takes place in the AC-DC converter acting as the diode rectifier in the double-way connection. This result in the generation of relatively large power losses for heat in the electronic converter, heating it, and leading to the need for cooling. However, the novel AC-DC converter acting as the transistor rectifier uses only a reverse conduction of MOSFETs as low ON-state voltage-drop electronic switches.

![Fig. 1 Comparison of the static characteristics of a power diode type D22-10-08 and a single MOSFET module type TU-3A FM600.](image)
2. Novel AC-DC Converter Operation

The silicon power diode is widely used as a component of the conventional AC-DC converter. When acting as a diode rectifier, it has a fundamental disadvantage: a relatively high voltage drop in the ON-state of a current conduction.

Fig. 1 shows that, in the range of 2-10 A of current conduction, an ON-state voltage drop across a single MOSFET FM600 module type TU-3A ($R_{DS(on)} = 1.5 \text{ m}\Omega$) is in the voltage range of 0.003-0.015 V, while under a type D22-10-08 power diode, the diode forward voltage is in the voltage-range 0.8-0.9 V. The advantage resulting from the replacement of power diodes with reverse-conducting MOSFETs is obvious, especially for low values of currents, when the voltage drops across the electronic switches are minimized. For example, for a rectified current of 10 A, it is more than 10-fold, and is connected with the same degree of change of decrease of power losses on heat dissipated by the electronic switches.

Reducing the power losses of heat dissipated by the electronic switches is connected not only with improving the energy efficiency of the AC-DC converter, but also a reduction in the size and cost of the heat sinks, as well as improved reliability, resulting in the lower operating temperature of electronic switches.

A MOSFET is an electronic switch with bilateral (bipolar) electrical conductivity and at the full control has a linear static characteristic $I_D = f(U_{DS})$, flowing the electric current in the first and third quarter of the output static characteristic.

In Refs. [8, 11, 15, 17, 18], on fundamental power electronics, as well as catalogs of the individual MOSFETs or their manufactured modules, there is included only single quadrant of the output static characteristic, and that is the I quadrant (positive)—$I_D = f(U_{DS})$ of the MOSFET (Fig. 2).

However, in the presented case, the transistor rectifier, the authors do not use the I quadrant (positive), but instead the III quadrant (negative) of the MOSFET static characteristics (Fig. 2) that is used for AC-DC rectifying, thus yielding the much lower voltage drop across the switches in comparison to the voltage drop of silicon power diodes.

Fig. 3 shows a simplified physical model of a conventional AC-DC converter generator (with an electronic converter, with opto-couplers, acting as a transistor rectifier in the double-way connection) for HSVs.
Electronic-switch control has been achieved in a simple way, by using the secondary diode rectifier, loaded on its output with the current stabilizer, which is realized on the JFET (junction gate field-effect transistor). The auxiliary diode rectifier is realised on LED opto-couplers: (D1+)-(D3+), (D1-)-(D3-), which acts as the switch controller, using the L0601 integrated circuit containing quad opto-couplers. Phototransistors of opto-couplers: (Q1+)-(Q3+), (Q1-)-(Q3-) have been used to control the rectifier’s electronic switches to generate the MOSFETs’ control pulses. The simulation physical model of the novel AC-DC converter in the double-way connection is shown in Fig. 4. This physical model, simulated as the AC-DC converter without the use of optoelectronic separation can be implemented as a high-power...
integrated circuit. This is what we as authors understand by the novel AC-DC converter.

The fundamental problem with the AC-DC converter’s electronic-switch control lies in the detection and identification of the sense of direction of the current flowing through each of the diodes D1+, D3+, D5+, D2-, D4-, D6- (Fig. 4) and the generation of control signals for the MOSFET’s gates, which at a predetermined time shunt a diode’s activity during the electrical-current conduction.

3. Mathematical Model of a Novel AC-DC Converter

A physical model of the novel AC-DC converter, acting as a transistor rectifier in a three-phase double-way connection is shown in Fig. 5.

The performance of the AC-DC converter in the double-way connection is often seen as a composition of two complementary single-way connections.

In power supply connection in a wye, assuming that, the potential of the point \( z \) is equal to the potential point \( 0 \), as shown in Fig. 5, the relationship between the AC-DC converter’s input and output voltages can be written as:

\[
\begin{bmatrix}
U_p \\
U_a
\end{bmatrix} = \begin{bmatrix}
C^{op} & C^{op} & C^{op} \\
C^{on} & C^{on} & C^{on}
\end{bmatrix} \begin{bmatrix}
U^p \\
U^n
\end{bmatrix}
\]

(1)

where, Eq. (1) defines the elements of the commutation matrix \( C^{kl} \), the existing commutating functions of appropriate commutating nodes "\( kl \)" , which in the case of an AC-DC converter operating as a transistor rectifier are functions of time. Because the commutation is done in those moments when the respective input terminals of AC-DC converter (Fig. 5) comes to equate the value of instantaneous values of voltage (e.g., voltage rectifier), or the instantaneous values of currents (e.g., current rectifier).

Omitting the process of commutation—a current switching follows at an infinitely short time, and adopts a zero value of resistance \( R_{DS(ON)} = 0 \) in the ON-state. Elements \( C^{kl} \) of the commutation matrix take two values:

\[
C^{kl} = \begin{cases}
1 & \text{an electronic switch in the ON-state} \\
0 & \text{an electronic switch in the OFF-state}
\end{cases}
\]

(2)

For the proper operation of the transistor rectifier in the double-way connection, the switch control in various branches should be such that:

\[
C^{op} + C^{on} \leq 1, \quad C^{op} + C^{on} \leq 1, \quad C^{op} + C^{on} \leq 1
\]

(3)

this means that, at any instant of time, the two electronic switches in each phase (or branch) of the AC-DC converter cannot simultaneously conduct an electrical current. Since \( U_n = -U_p \) and \( U_{pn} = U_p - U_n \), then Eq. (1) for the AC-DC converter’s output voltage can also be written as:

\[
U_{pn} = U^p = \begin{bmatrix}
C^{op} - C^{on} & C^{op} - C^{on} & C^{op} - C^{on}
\end{bmatrix} \begin{bmatrix}
U^p \\
U^n
\end{bmatrix}
\]

(4)

The AC-DC converter’s output voltage in the double-way connection as a function of the input line voltages at power supply connection in wye, as shown in Fig. 5.

4. Computer Simulation and Analytical Studies of the AC-DC Converter in the Double-way Connection

An important advantage of the novel AC-DC converter under consideration is the use of reverse-conducting MOSFETs in order to reduce voltage drops across the electronic switches. The physical model of the novel AC-DC converter in the double-way connection, without the use of optoelectronic separation, and which does not require a separate power supply is easy to implement in integrated technology, as shown in Fig. 4.

In order to perform a rapid computer simulation of novel the AC-DC converter, we adopted a simplified simulated physical model of the three-phase AC power source.
In Figs. 6-9 selected, characteristic waveforms during normal operation are shown, both in the AC-DC converter’s circuits, as well as the MOSFETs gate-pulses control circuits.

As an example, Figs. 6 and 8 show the waveforms of the neutral voltage in relation to ground, power-supply, voltages and the control voltage across the gate of the MOSFET. When the transistor is given the function of current conduction, the shunt freewheeling diode current is much smaller.

Fig. 8 shows the waveforms of the currents flowing through the AC-DC converter’s electronic switches, and the voltages across switches, both in the ON-state as well as OFF-state (blocking).

At the same time, the nominal values (ratings) of supply AC voltages were chosen as those corresponding to the high-performance AC-DC converter generator’s average load in real conditions. For a comparison of the currents and voltage drops, as well as to estimate the power losses on the conventional AC-DC converter acting as a diode rectifier’s electronic switches and novel AC-DC converter’s switches, we performed the
following experiment: We conducted a computer simulation of the novel AC-DC converter, with one of the MOSFETs disabled (M6 in Fig. 4).

The function of the current conduction in the AC-DC converter is taken over by the D6-diode.

The waveform shown in Figs. 8 and 9 shows the difference in the voltage drops between the D6-diode and MOSFET current conduction in the adjacent branch of the double-way connection (part of the waveform under the of the zero-axis). Moreover, there occurs much lower voltage drop across the MOSFET during current conduction, compared to the voltage drop across the conventional AC-DC converter with power diodes, causing a significant reduction in heat losses, and the difference in the voltage drops across the electronic switch results in an increase in the output voltage, as shown in Fig. 9 [20-23].

Significant reduction in voltage drops across the MOSFET, compared to voltage drops across the power diode, is confirmed in the experimental studies given below.

5. Experimental Studies

An AC-DC converter of the advanced AC-DC
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Fig. 9  Selected waveforms of the novel AC-DC converter’s voltages, currents and power losses to heat (comparison of electronic switches’ conduction).

Committor generator is made on the six reverse-conducting MOSFETs integrated module in a single enclosure using a new generation FM600 type TU-3A Mitsubishi electric semiconductor (Fig. 10).

The main advantages of this module compared to others of this kind are:

- very low ON-state resistance $R_{DS(ON)} = 1.5 \text{ m\$\Omega\$}$ (typical) $R_{DS(ON)} = 2.2 \text{ m\$\Omega\$}$ (max);
- fast freewheeling diodes, parallel to the MOSFETs, built-in thermistor temperature sensor for a temperature control module;
- convenient terminals for connection to the electrical power supply;
- favorable load parameters: $U_{DS} = 150 \text{ V}$, $I_D = 300 \text{ A}$ (maximum current pulse 600 A), each of the six built-in MOSFETs.

The maximum power loss through dissipated heat is of 960 W, and the instantaneous power load may reach 1,300 W. Each of MOSFETs of the module is an almost ideal electronic switch. Its drain current in OFF-state cannot exceed the value of 1 mA, and the saturation voltage $U_{DS}$ at a current conduction of 300 A, and at 25 °C is of 0.66 V.

Figs. 11-15 show the results of bench experimental studies in the form of voltage waveforms on electronic switches of novel and conventional AC-DC converters in double-way connections.

Below the zero-axis in the oscillograms (Figs. 11a and 11b), one can see the voltage on the switch with the positive value (during ON-state), while above this zero-axis—the reverse voltage, which due to the relatively large maximum value of this voltage has been recorded only partially.

Comparing the voltage waveforms for the
conventional and novel AC-DC converters’ electronic switches, one can easily notice a significant decrease in the voltage drop across the conductive MOSFET (Fig. 11b)—the voltage-drop value, while applying gate control signal is very low, almost imperceptible, while for the conventional AC-DC converter (Fig. 11a), it is significant, around 0.8 V.

The presence of a significant voltage drop across the conventional AC-DC converter’s electronic switches causes them to overheat and causes deterioration of energy efficiency, as well as the need for effective ventilation of the conventional AC-DC converter, which generates more power dissipation caused using an additional fan. Fig. 12 shows the voltage waveforms on the electronic switch and switch’s gate voltage of the conventional and novel AC-DC converters.

The waveforms depicted in Figs. 12-14 show that, through controlling of the AC-DC converter’s electronic switches, one can achieve a substantial improvement of the energetic parameters. These minimize, in the analogous degree, the power losses and increase an efficiency of the AC-DC converter, and thus the energetic efficiency. In this case, the rectification of the armature phase currents is almost perfect.

Fig. 15 shows the novel AC-DC converter-driver’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 advanced AC-DC converter generator for connected HSVs.
Fig. 13  Influence of switches’ control pulses of the novel AC-DC converter upon on voltage-drop value during ON-state.

Fig. 14  Voltage waveforms across the electronic switch of the transistor rectifier in the double-way connection during an advanced AC-DC converter generator operation at an increase of an AC-DC converter generator’s shaft rotational speed and a load current of 20 A.

Fig. 15  View of the novel AC-DC converter-driver’s plate based the integrated IR2136, and its installation in the terminal box of the advanced AC-DC converter generator for HSVs.

The driver plate is designed with the assumption that, the controller’s 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 driver. In this way, the resistance, inductance and capacitance parasitic values are reduced, and a more compact design of the modified electronic AC-DC converter of the electrical machine is achieved.
6. Conclusions

The paper presents the principle of the high-performance AC-DC converter generator with the novel AC-DC converter with in a double-way connection.

The results of computer simulation waveforms of power and voltages are also given as well as of the currents of the novel AC-DC converter in three-phase double-way connections using PSPICE (personal computer simulation program with the integrated circuits and emphasis). The possibility of using a novel AC-DC converter in low-voltage power supply systems is indicated. In comparison with the conventional AC-DC converters (realized on the silicon power diodes), the novel AC-DC converter exhibits a number of advantages, namely: They have a much lower forward-voltage drop, and therefore less power losses on heat, and better energetic efficiency and reliability. These AC-DC converters can be made in the form of a MC (modular circuit) or an ASIC (application specified integrated circuit). Computer simulation allowed for the imitation of any selected waveforms of voltages and currents in the novel AC-DC converter. This simulation also confirmed the benefits of using a high-performance AC-DC converter generator with a novel AC-DC converter (with no opto-couplers) instead of a conventional AC-DC converter (with opto-couplers), those benefits being the higher energetic efficiency (reduction of power losses caused by the heat in the electronic converter) and the associated reliability.

References


