Method for Calculating the Power Circuit Characteristics of the Isolated DC-DC Converters for Electric and Hybrid Vehicles

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Abstract
Advanced vehicles, i.e. electric and hybrid cars, with the high-voltage battery pack as the primary power source, require conversion of the battery DC voltage into the low onboard DC voltage. Safe operation of the system can be achieved with galvanic isolation of the high-voltage source and onboard consumers. This article presents the main circuit solutions for car DC voltage conversion and considers some of the issues related to the design of the isolated DC-DC converters, as well as a method and key principles for calculating the converter characteristics.

Keywords: Battery Pack, Converter, Electric Traction Drive, Electrical Equipment, Electric Car, Transformer, Voltage Converter

1. Introduction
Growing prices for hydrocarbons, as well as tightening standards for toxic emissions are responsible for high demand and, as a result, increased output of economic and eco-friendly vehicles – cars with combined power systems and electric cars1.

The electric generator driven by the internal combustion engine (ICE) is an essential part of a conventional vehicle. ICE works when a car moves or comes to a stop. It ensures continuous operation of the generator supplying power to the low-voltage onboard consumers and charging the starter battery. However, advanced vehicles, including electrically driven transport and industrial vehicles, with the high-voltage Battery Pack (BP) as the primary power source, require conversion of the battery DC voltage into the low onboard DC voltage. Moreover, it makes sense to increase the BP traction voltage to minimize current loads in the electrical windings and reduce weight and size of the electrical traction systems. On advanced vehicles, the electrical systems that drive the energy generator do not operate continuously (e.g., the generator drive ceases to function as soon as the car comes to a stop). Therefore, the above power supply circuit is inapplicable to electric and hybrid vehicles. The problem can be easily resolved by installing DC-DC converters. The buck converter charges the low-voltage battery pack and feeds power to the onboard devices, while the boost converter powers the electric traction equipment.

The article introduces two main circuit solutions for DC voltage conversion in the vehicle power systems and considers some of the issues related to the design of the transformer reversible DC-DC converters, while examining the application of the existing methods for calculating the high-frequency toroidal transformers for the electric traction systems.
2. Concept Headings

2.1 Main Circuit Solutions for DC-DC Converters

A growing number of electrically driven vehicles (cars with combined power systems and electric cars) along with the revised requirements to their traction and dynamic performance increase the need for additional voltage converters. They are applicable to the transport and industrial vehicles operating indoors. Vehicles with ICE replaced by the electric traction motor make operations more eco-friendly ensuring environmental safety.

There are various circuit solutions for conversion of the primary source DC voltage in the vehicle power systems. Basically, two main approaches can be distinguished:

- transformer less converters (buck and boost converters);
- transformer converters.

Each voltage conversion method has its own advantages and drawbacks. The final decision depends on the peculiarities of the DC-DC converter application.

The need for bidirectional (reversible) operation of the DC-DC converter as part of the electric traction system is explained by the fact that the vehicle traction system, apart from traction, shall ensure counter current braking with power recuperation into the battery pack. Thus, to ensure traction the DC-DC converter shall convert (step up) the battery voltage into the input DC voltage of the traction inverter (direct conversion). Similarly, to ensure recuperation braking, the DC-DC converter shall convert (step down) the voltage rectified by power diodes of IGBT modules of the traction inverter into the battery charge voltage (reverse conversion).

A perfect example of transformer less DC conversion shall be the DC-DC converter incorporated into the electric traction system of Toyota Prius, the car with a hybrid power system. In the 2004 Prius, the input voltage of the power inverter is 500 V, whereas the rated voltage of the high-voltage battery pack is 201.6 V. The converter comprised of the throttle and the intelligent power transistor module ensures bidirectional DC conversion. For the power circuit of the DC-DC converter, see Figure 1.

The DC-DC converter operating principle is based on the cyclic process in which switching of the IGBT module transistors and a sequence of throttle charge and discharge phases occur to allow capacitive energy storage and traction. Two power transistors ensure bidirectional DC conversion.

The DC-DC converter incorporated into the electrical traction system of Toyota Prius made it possible to increase the operating AC voltage of the electrical systems and reduce the winding loads and weight and size of the systems.

The main drawback of the above diagram is coupling of the DC-DC converter input and output circuits. The full-bridge topology (Figure 2) has no such drawback. It is the main circuit solution for the high-voltage converters with galvanic isolation of the power sources providing reversible DC conversion. The main components of the DC-DC converter in the diagram below shall include the high-voltage transformer (HFT), low-voltage bridge inverter (LVI) and high-voltage bridge inverter (HVI). The DC-DC converters allowing bidirectional conversion are often called dual active bridge converters.

To function as a car generator being the main component of the power supply system of an ICE-based vehicle, the traction system shall require the DC-DC converter to convert (reduce) the high voltage of the traction battery into the direct voltage needed to charge the low-voltage battery pack and feed power to the onboard DC consumers. In this case, there is no need for reversible power conversion. However, there is a need for galvanic isolation of the low and high voltage circuits. The transformer circuit (Figure 3) perfectly fits this purpose. Unlike the previous circuit, it has one inverter instead of two and a rectifier.
Figure 2. Power circuit of the bidirectional (reversible) DC-DC converter: LVI, HVI – low-voltage and high-voltage inverters; HFT – high-voltage transformer; VT – IGBT- transistors; VD – semiconductor diodes; С – electric capacitors, R – precharge resistor.

Figure 3. Power circuit of the unidirectional DC converter: Uin – high input DC voltage; Uout – low output DC voltage; HVI – high-voltage DC inverter; HFT – high-voltage buck transformer; rectifier; VT – IGBT- transistors; VD – semiconductor diodes; С – electric capacitors.

The solution has the following advantages:

- galvanic isolation of the low and high voltage circuits;
- efficient use of the transformer core sitting idle due to no magnetic-flux DC component failing to generate the electromotive force and simply loading the core;
- symmetrical bidirectional DC conversion depending on the operating modes, use of the primary power source (Picture 2);
- improved voltage buildup factor compared to the transformer less circuits;
- relative simplicity of the circuit and control algorithms for the power transistor keys;
- stand-alone self-contained units facilitating equipment unification;
- possibility of DC-DC converter modification for different capacities and sizes without significant design alterations.

The main drawback of the solution is a greater number of the power transistor diode modules and lower weight and size compared to the transformer less circuits.

3. Method and Result

3.1 Method for Defining and Calculating the Characteristics of the Buck DC-DC Converter Power Circuits

The theoretical part of this article is devoted to the DC-DC converters designed in accordance with the isolated converter topology. DC-DC converters are crucial for the power supply of the onboard electrical equipment of advanced vehicles. This article presents a method for defining and calculating the characteristics of the buck DC-DC converters. The method shall include the following steps:

- Assessment of the electrical characteristics of the low-voltage consumers and their operating modes.
- Calculation of the rated load of the DC-DC converter.
- Determination of the DC-DC converter required capacity (checking the converter choice for correctness)
- Calculation of the electrical balance under the basic vehicle operating modes (if needed).
• Determination of the characteristics of the DC-DC converter power circuit main components (high-frequency transformer, power semiconductor transistor diode modules).

This method can be used for selecting the already existing DC-DC converters or designing power circuits for the new DC-DC converters.

3.2 Operating Modes of the Power Consumers Installed in Electric and Hybrid Cars, Calculation of the Rated Load of the DC-DC Converter

The power consumers installed in electric and hybrid cars can be divided into four main groups:

Group 1. Long-time operation consumers. Some of them operate throughout the entire period of the car movement, e.g. electric power steering system, onboard electronic and control devices, while others are on only during night driving (headlights, clearance lamps).

Group 2. Temporary operation consumers. They operate as required during the limited though rather long periods of time depending on the road and weather conditions (air conditioning, brake lights, turn indicator, window glass heating, windscreen wipers, etc.).

Group 3. Short-term operation consumers (audio alarms, emergency lights, window regulators). Their operating time can range from a split second to a few seconds, whereas the total operating time of one consumer does not normally exceed one minute in one drive.

Group 4. Consumers turned on at car parks (trunk and interior lights, onboard electronics, alarm signals).

The current consumption of the power receivers depends on the driving conditions. For example, if an electric or hybrid car travels along a highway at night in the winter time, a maximum number of power consumers is engaged (maximum power load). Some consumers operate in the intermittent mode or continuous mode with changing current values (e.g., electric power steering system). The equivalent current of such consumers shall be calculated as an arithmetical average when estimating the charge balance. Thus, the power consumers are characterized by a random load and a wide range of operating modes.

All possible operating conditions of the electric vehicles equipped with the electric heating and air conditioning systems can be classified as the standard operating modes taken into consideration when calculating the power balance:

a) nighttime winter highway driving;
6) daytime winter highway driving;
в) nighttime winter town driving;
г) daytime winter town driving.

For hybrid cars, the above modes shall be verified to enable air conditioning in the summer time.

To create a controllable microclimate in electric cars, with the traction battery as the primary power source, as well as to enhance ICE efficiency in hybrid cars, the electric climate control systems shall be used. The electric heating and air conditioning systems are normally powered by the high-voltage battery pack. It allows for the required climate control capacity at the minimum power consumption with no limitation of the DC-DC converter capacity. However, we should take into account the increased load of the DC-DC converter caused by the auxiliary low-voltage devices and electric seat and window glass heating systems.

For standard vehicle operating modes, the random consumer current values prove to be statistically stable and reasonably consistent. This consistency shall be defined as the ratio of the consumer operation time factor to vehicle power unit operation time $k_t$, as well as load factor $k_l$ for the consumers having several operating modes. Load factor $k_l$ shall mean the ratio of the actual electric power consumed under different operating modes to the electric power required for the maximum load operation of the consumer during the same total operation time.

The rated load current shall be defined as the sum of the equivalent currents of the power consumers operating simultaneously in the mode under consideration:

$$I_{Load} = \sum I_{eq} = \sum I_{cons} \cdot k_t \cdot k_l$$  \hspace{1cm} (1)

where $I_{eq}$ – consumer equivalent current, A; $I_{cons}$ – consumer rated current depending on its technical characteristics, A; $k_t$ – consumer operation time factor; $k_l$ – load factor.

Multiplying of $k_t$ factor by $k_l$ factor shall produce the power demand factor.

The consumer current shall be determined at the power supply voltage (DC-DC converter voltage) of 13.5 V or 27 V for 12 V or 24 V electrical equipment, respectively.

The correctness of the DC-DC converter capacity choice shall be checked under maximum load when the long-term operation power receivers installed in electric or hybrid vehicles simultaneously take maximum power
from the DC-DC voltage converter. For electric cars, it will be nighttime winter highway driving. For hybrid cars, either nighttime winter highway driving, or summer time driving with air conditioning depending on the power system configuration.

The consumer rated current under maximum load shall be calculated by formula 1.

If operated under maximum load, the generator shall have the capacity ensuring a virtually zero power balance and an additional charge of the auxiliary low-voltage battery with the steady charge current.

Then, the maximum DC-DC converter current required for maintaining the stable charge balance in this mode shall be estimated as

\[ I_{DC\text{max}} = \frac{I_{\text{Loadmax}}}{1 - T_{\text{bat}}} \],

(2)

where \( I_{\text{Loadmax}} \) – rated current of the consumers switched on when a car moves or is parked with its engine running under maximum load, А; \( T_{\text{bat}} \) – relative duration of the auxiliary low-voltage battery discharge for electric or hybrid cars.

It should be noted that the role and characteristics of the auxiliary battery pack depend on the power supply of the low-voltage electrical equipment mainly in the modes involving disconnection of the traction system from the high-voltage power source. Among them, the mode ensuring stable power supply to the low-voltage circuits when the vehicle is parked, as well as power supply to the alarm systems and other devices important in terms of traffic safety.

In view of the above, the required capacity of the buck DC-DC converter shall be defined as

\[ P_{DC\text{min}} = U_{\text{DC\text{Rated}}} \cdot I_{DC\text{max}} \]

(3)

where \( U_{\text{DC\text{Rated}}} \) - DC-DC converter rated voltage (is taken to be 13V…14V or 27V…28V for 12 V and 24V electrical equipment).

To evaluate whether the DC-DC converter can ensure the nominal operation of the onboard consumers and the charge of the auxiliary battery pack, the calculation of the power balance in the basic operating modes shall be made. The calculations shall show the amount of electrical energy required to power the onboard equipment in the most energy-intensive modes.

After the minimum required capacity of the DC-DC converter is calculated, the characteristics of the main converter components shall be determined.

### 3.3 Determining the Characteristics of the Main Components of the DC-DC Converter Power Circuit: Defining the Parameters of the High-Frequency Transformer as Part of the DC-DC Converter

The high-frequency power transformer (HFT) is the main component of the DC-DC converter with galvanic isolation. The high-frequency impulse voltage allows for the reduction of the converter weight and size.

A method for calculating the high-frequency toroidal transformer for the full-bridge DC-DC converter is presented below. According to this method, the following parameters and characteristics of the high-frequency transformer shall be successively determined:

- HFT size capacity.
- Structural parameters of the magnetic core and physical characteristics of the core material.
- Maximum induction in the HFT core.
- Transformer rated size.
- Magnetic core size and geometrical characteristics.
- Number of transformer winding turns.
- Power losses in the magnetic core.
- No-load current in the HFT primary winding.
- Winding structural parameters and HFT weight.

The following DC-DC converter and transformer parameters are normally taken as the source data for the calculations:

- \( U_{d1} \) – HFI inverter rated input voltage;
- \( U_{d2} \) – rectifier rated output voltage;
- \( I_{1\text{rms}}, I_{2\text{rms}} \) – permanent and peak current loads in the HFT primary and secondary windings;
- \( f \) – voltage frequency of the transformer windings;
- \( U_{1}, U_{2} \) – peak voltages in the HFT primary and secondary windings;
- \( \Delta U_{d1}, \Delta U_{d2} \) – voltage drops across the inverter and rectifier circuit elements;
- \( k_{\text{form}} \) – HFT input voltage form factor;
- \( t_{\text{imp}} \) – HFT input voltage impulse duration;
- \( q \) – HFT input voltage relative impulse duration;
- \( \gamma \) – stacking factor.

### 3.4 Transformer Size Capacity

The HFT (rated) size capacity shall be estimated as the half-sum of the electromagnetic capacities of the primary and secondary transformer windings:

\[ p_{\text{HFT}} = \frac{U_{1\text{rms}} \cdot I_{1\text{rms}} + U_{2\text{rms}} \cdot I_{2\text{rms}}}{2 \cdot \eta} \],

(4)
where $U_{1\text{rms}}, I_{1\text{rms}}, U_{2\text{rms}}, I_{2\text{rms}}$ – the effective voltage and current in the HFT primary and secondary windings; $\eta$ – transformer efficiency factor. Size capacity is a key parameter for transformer calculations.

### 3.5 Selecting the Design and Material for the HFT Magnetic Core

For the high-frequency transformer of the reversible DC-DC converter, it makes sense to use a ring-shaped core in a protective container. To justify the choice of the ring-shaped magnetic core, the following advantages of toroidal HFTs can be mentioned:

- minimum leakage inductance contributing to lower voltage surge in the inverter power keys, as well as reduced noise levels and transformer output resistance;
- relatively low manufacturing cost of the core;
- a wide variety of domestic cores;
- minimized weight and size, rational use of the winding surfaces.

The choice of the magnetic core in the protective container is explained by the operation conditions of the vehicle DC-DC converter.

The transformer core material shall have low specific magnetic losses and guarantee operability at high frequencies of the winding voltage and current ($f \geq 5000$ Hz). Nanocrystalline ferrous alloys, e.g. GM414, meet the above requirements. For the physical properties of GM414 alloy (Table 1).

For the core magnetization curves, see Figure 4.

Maximum induction in the HFT core ($W$) shall depend on:

- saturation induction $B_S$;
- core non-saturation conditions.

For the balanced mode of the transformer operation (symmetric magnetization reversal of the core – full hysteresis loop), the maximum induction may equal: $0.5 \, B_s \leq W \leq 0.75 \, B_s$

The rated transformer size shall be defined as

$$S_C S_W \geq \frac{50 \cdot P_{\text{HFT}}}{f \cdot \Delta B_m \cdot \eta \cdot j \cdot k_C \cdot k_w \cdot k},$$  \hspace{1cm} (5)

where $S_C$ and $S_W$ – cross-sections of the core and core window, respectively, cm$^2$; $P_{\text{HFT}}$ – transformer rated (size) capacity, VA; $f$ – winding voltage frequency, Hz; $\Delta B_m$ – maximum range of the induction change in the core; $k_C$ – stacking factor; $k_w$ – wire lay for the window area ($k_w=0.5$ for high-power transformers); $k_{\text{form}}$ – HFT input voltage form factor ($k_{\text{form}}=1$ for rectangular voltage); $\eta$ – HFT efficiency ratio; $j$ – current density in the winding wires.

### Table 1. Physical properties of magnetic core GM414

| Parameter                                      | Value     |
|------------------------------------------------|-----------|
| Magnetic induction $B_{800}$ ($B_s$)           | 1.17 T    |
| Relative magnetic permeability $\mu_{0.08}$ at the magnetic field strength of 0.08 A/m | 60,000    |
| Relative maximum magnetic permeability $\mu_{\text{max}}$ | 300,000   |
| Coercive force $H_c$                           | 0.8 A/m   |
| Remanence ratio $Br/B_{800}$                   | 0.6       |
| Density                                        | 7400 kg/m$^3$ |
| Specific magnetic losses $P_{\text{spec}}$ for the frequency range of $f = 3...200$ kHz at magnetic induction $B_m$ | $P_{\text{spec}} = 5.5 \cdot 10^{-6} \cdot f^{1.7} \cdot W^2$ W/kg |
| Stacking factor $k_C$                          | 0.7       |

### Figure 4. Static and dynamic curves of GM414 core magnetization.

3.5.1 Magnetic Core Size

The type of the ring-shaped magnetic core shall depend on transformer size $S_C S_W$ and the core design. The magnetic core parameters, including their geometrical characteristics, are usually specified in manufacturer’s catalogs.
3.5.2 Number of the Transformer Winding Turns

The number of primary and secondary winding turns \( w_1 \) and \( w_2 \) shall be estimated taking into consideration the maximum magnetic induction in the core, transformer size and input voltage characteristics:

\[
w_1 = \frac{q \cdot U_1 \cdot 10^4}{2 \cdot f \cdot S_C \cdot K_C \cdot K_{form} \cdot B_m},
\]

\[
w_2 = \frac{U_2}{U_1}.
\]

3.5.3 Magnetic Core Loss Estimates

The magnetic core losses shall be calculated taking into account the specific magnetic losses indicated by the manufacturer for the winding voltage frequencies and maximum magnetic induction:

\[
P_C = P_{spec} G_C
\]

where \( P_{spec} \) – specific magnetic losses, W/kg; \( G_C \) – magnetic core weight, kg.

For GM414 core material, according to the source data

\[
P_{spec} = 5.5 \cdot 10^{-6} \cdot f^{1.7} \cdot B_m^2
\]

Magnetic core weight

\[
G_C = V \cdot \rho
\]

where \( V \) – core size, m\(^3\); \( \rho \) – core material density, kg/m\(^3\).

3.5.4 No-load Current in the HFT Primary Winding

\[
I_n = \sqrt{I_{na}^2 + I_{nr}^2},
\]

where \( I_{na} \) and \( I_{nr} \) – active and reactive components of no-load current \( I_{nl} \) of the transformer, respectively, A. Here,

\[
I_{na} = \frac{P_C}{U_1}.
\]

\[
I_{nr} = \frac{H_m \cdot l_{mean}}{w_1},
\]

where \( l_{mean} \) – length of the magnetic core centerline, m; \( w_1 \) – number of the primary winding turns; \( H_m \) – strength in A/m at maximum induction \( B_m \). It shall be calculated taking into consideration the core magnetization curve, rated \( B_m \) and frequency \( f \).

3.6 Winding Design Parameters and HVT Weight

The (copper) wire diameters shall depend on the rms currents and maximum current density in the respective winding wires. The HFT weight shall be defined as the sum of the magnetic core weight and the transformer winding weight.

The above analytical dependencies allow us to assess the weight and size of the DC-DC converter and determine the main characteristics of the converter components, including the key component – the high-frequency transformer when designing the transformer DC-DC converters.

3.7 Determining the Characteristics of the Main Components of the DC-DC Converter Power Circuit: Power Semiconductor Transistor Diode Modules

The DC-DC converter required characteristics, including the maximum input and output voltages and current loads and module switching frequency shall be primarily taken into consideration when selecting the power semiconductor components of the DC-DC converter. There are several principles of the IGBT module selection:

3.7.1 Collector-emitter Voltage

To ensure high reliability, the IGBT module shall have the maximum permissible collector-emitter voltage exceeding the module input voltage by 60-70 %. However, the voltage shall not exceed the above levels; otherwise the IGBT dynamic losses will increase.

3.7.2 Optimum Switching Frequency

To minimize the total losses, the IGBT and rectifying diodes shall be selected depending on the operating frequency of the DC-DC converter transistor key switching. The operating frequency shall be within the optimum IGBT switching frequency range.

3.7.3 Collector Current

To ensure high reliability, the collector peak current shall not exceed 70 ÷ 80 % of the maximum permissible collector-emitter direct current. After the module is selected, the heat mode of the module shall be determined. Its
heavy-duty operation shall be considered on the condition that crystal maximum temperature $T_j$ (in °C) cannot exceed 80% of the maximum permissible temperature.$^8$

4. Discussion

Upgrade of the electric traction system components, development of the existing and implementation of new technical solutions for advanced vehicles along with improved traction and dynamic performance and reduced weight and size of the electric traction systems create the need for DC-DC converters. The peculiarity of the onboard power system is that it can ensure reversible (bidirectional) DC conversion and galvanic isolation of the DC sources. The calculation of the optimal characteristics of the heavy-current DC-DC converters for electric cars and cars with combined power systems is highly important, since now there are no single theoretically substantiated vehicle-oriented approaches to calculating transformer and transformer less DC-DC converters and their power components. The existing theory mainly applies to the low-duty converters used in electronics and is not adapted for the electric power units.

5. Conclusion

The article considers some of the issues related to the design of the DC-DC converters and presents the key dependencies that can be used for the estimation of the parameters and characteristics of the vehicle reversible DC-DC converters and thus solve the problem under consideration.

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