Isolated step-down DC -DC converter for electric vehicles

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Abstract. Modern motor-vehicle industrial sector is moving rapidly now towards the electricity-driving cars production, improving their range and efficiency of components, and in particular the step-down DC/DC converter to supply the onboard circuit 12/24V of electric vehicle from the high-voltage battery. The purpose of this article - to identify the best circuitry topology to design an advanced step-down DC/DC converters with the smallest mass, volume, highest efficiency and power. And this will have a positive effect on driving distance of electric vehicle (EV). On the basis of computational research of existing and implemented circuit topologies of step-down DC/DC converters (serial resonant converter, full bridge with phase-shifting converter, LLC resonant converter) a comprehensive analysis was carried out on the following characteristics: specific volume, specific weight, power, efficiency. The data obtained was the basis for the best technical option - LLC resonant converter. The results can serve as a guide material in the process of components design of the traction equipment for electric vehicles, providing for the best technical solutions in the design and manufacturing of converting equipment, self-contained power supply systems and advanced driver assistance systems.

1. Introduction
Communication systems sensitive devices and navigation systems of unmanned vehicles and cyber security of unmanned driving – it is impossible to imagine an unmanned electric transport vehicle without these essential components. Isolated step-down voltage converter is very important component too. Thanks to advanced technical solutions in the field of converting equipment, and in particular in the field of automotive converters, electric vehicle can fully meet all the requirements of safety, environmental and energy efficiency as well as automatic control.

Problems of energy saving and efficiency come to the fore in almost all applications, including electric vehicle: the higher efficiency of the conversion devices, the more the range distance of electric car, so this direction is important. One of the most important ways to improve the efficiency of the device is to increase the efficiency of DC-DC converters of the power supply. The losses in the Converter are divided into the switching (dynamic) that occur when power switches are working in the key mode and the losses in conductivity (resistive). The method to decrease the resistive losses is decreasing the amplitude of the ripple current. There are dynamic losses in this scheme. These losses can be minimized through circuit design and software.

Reducing losses not only increase the energy efficiency of the Converter and the electric car, but also can simplify the design of the Converter, as it will decrease the heating of its elements. [2]
Exploring the existing modern market of automobile DC/DC converters, it is possible to generate requirements for the design of energy-efficient and competitive Converter:

Table 1. Parameters of the modern converter.

| The direction of the transformation: | From high voltage to low |
|-------------------------------------|--------------------------|
| Efficiency:                         | >92%                     |
| Input voltage:                      | 220-410 V                |
| Output voltage:                     | 12-16 V                  |
| Power:                              | 2.5 kW                   |
| The minimum power density:          | 1 W/cm³                  |
| Capacity (without radiator cooling) | 2.5 liters               |

2. Analysis of topology

2.1. Full bridge phase-shift topology

Full bridge PWM Converter is shown in figure 1. The primary circuit is built on the principle of full bridge, secondary rectifier - with tap from mid point, and a series connected inductor required to operate this type of converters with PWM control.

![Figure 1. A simplified diagram of the full bridge Converter.](image)

For better understanding of the operation principle of this Converter we should consider the circuit shown in figure 2. It is the basis of all step-down regulators, where the power circuit includes a series connected inductance.
We assume that the transistor and the diodes are perfect, and the switching frequency is so high that the voltage across the load not depend on switching time. In addition, we will consider the steady operation when the load current, the input and output voltages do not depend on switching time. [1]

Then the operation will be described by the equation:

$$U_{out} = U_{in} \cdot \gamma$$

Where $\tau_1$ – time of the closed state of the key, $\tau_0$ – time of the open state of the key, $\gamma$ is the duty ratio. [1]

There is a transformer (figure 1) with a transformation ratio $k$, then the equation will be as follows:

$$U_{out} = U_{in} \cdot \frac{\tau_1}{\tau_0 + \tau_1} = U_{in} \cdot \gamma$$

From this equation it is clear that the output voltage is not regulated in frequency. The output voltage is regulating by timing relationships of pulse and pause. Pulses to the primary winding of the transformer are supplied by closing the keys diagonally: in even half-cycles, the keys VT1 and VT4 are closed, and in odd ones, VT2 and VT3.

There are static and dynamic losses on the scheme shown in figure 1.

Dynamic losses in the transistor are caused by the considerable current flowing. Transistor for a short time is in the active mode, this is a cause of considerable current.

However, there is energy ten times greater than in the saturation state. It is clear that the released energy of switching operation, is proportional to the duration of the transient phenomena. So, to minimize released energy high speed transistors must be used. To reduce dynamic losses (figure 3) ZVS method is using (zero voltage switching), i.e., switching with zero voltage across the transistor. These overvoltages are due to resonant processes in the moments of switching. With the result that, considerable power produces in the time period of the active state of the key (the moment of transition from cutoff to saturation or Vice versa). ZVS can significantly reduce this power, which is clearly seen in figure 3 and figure 4 and turns “hard” switching to “soft”.

Figure 2. Lowering scheme (a) and timing diagram (b).
However, the mode switching at zero voltage can only be received under certain loads. This is due to the fact that despite the obvious symmetry of both half-bridges the topology and the control signals operation modes are significantly different. For the slave (second) half-bridge ZVS mode can only be received when the load is larger than a certain threshold. Decreasing this threshold is achieved only by increasing the leakage inductance of the transformer (or an inductor in series with the transformer), which inevitably leads to increased losses. The second important drawback: there are times when the primary winding is short-circuited at intermediate phase shifts (i.e., greater than 0° but less than 180°) through the two opened keys. At this time there is a sufficiently large current (circulating current), which cause the losses of course.

Static losses are due to the voltage drop on the circuit elements under the action of the current flowing during the periods of time between shifts. It is important to note that due to the skin effect high frequency current heats the wires. Frequency current is considerably greater than the permanent current of the same magnitude. The static losses in the switch are minimized by choosing transistors with low resistance in saturation mode, and Schottky diodes (with low direct voltage drop). Synchronous rectification is widely used method to create powerful converters with low output voltage. The main idea is to replace the diodes on the secondary side with the field effect transistors (MOSFET), which have a significantly smaller voltage drop in the open state. In this case the special scheme applies to synchronize the working secondary side with the main side.

There are surges in the hard switching of transistors because of difficult implementation of ZVS on the secondary side. To reduce the threat of the surge (dangerous, because it can damage the transistors and radiates noise) bulky snubbers and filter chokes were applied.

In 2011, the firm VALEO has designed the first prototype of such a Converter shown in figure 5.

![Figure 5. VALEO’s Converter.](image-url)
In the figure 5 one can notice two large chocks are designed to filter from noise. They take up very much space, so specific volume suffers greatly. The sizes of the inductors are determined by a large current in the power circuit.

Due to the hard switching of the transistors in the secondary circuit, the frequency is limited to 100 kHz, which limits the using of miniaturized magnetic components in this Converter. This Converter is based on full bridge circuit with phase shift and has an efficiency of 92%, with a volume of 4.8 liters and specific volume of 0.61 W/cm³.

We can conclude that this topology is not suitable as parameters of the volume and efficiency do not meet modern requirements shown in the table 1.

2.2. The series resonant topology

Half-bridge series resonant Converter (shown in figure 6) is simple and well-known scheme for HV/LV conversion.

The most effective way to obtain high levels of specific power and specific volume is to increase the operating frequency so that the size of magnetic components has been significantly reduced. Resonant converters can operate at high frequencies due to the very small switching losses. In converters of this type the adjustment of the output voltage occurs by PFM (pulse-frequency) modulation. Half-bridge series resonant Converter is simple and well-known scheme for HV/LV conversion.

Resonance circuit consists of inductor Lr, resonant capacitor Cr and the transformer. The transient response represented by the following equation:

\[ G = \frac{1}{1 + j\frac{\pi Q}{f_s}} \]  

(3)

where \( f_r = \frac{1}{2\pi\sqrt{L_rC_r}} \), \( f_s \) – switching frequency. \( Q \)- quality, \( Q = \frac{L_r}{R_{ac}} \) ; \( R_{ac} \) – quality, \( R_{ac} = \frac{R_{out}}{n^2\pi^2} \).

The circuit of the load rectifier is connected in series with the LC resonant circuit, as shown in figure 6. In this configuration, resonant circuit and load operate as a voltage divider. The impedance of the resonant circuit is changing, when the frequency of the voltage Vd at the output of the half bridge is changing. The input voltage is divided between this impedance and the reflected load resistance. Thanks to voltage divider, the gain of the DC voltage LC serial resonant Converter is always <1. In the state of low load, its impedance is very large in comparison with the resistance of the resonant circuit; all the input voltage is on the load (it is clear from the graph in figure 7 for the curve Q = 1 (10 % load)).
The transfer function of voltage to a series resonant LC Converter.

The output voltage adjustment is practically impossible in this mode. Theoretically, frequency should be infinite to regulate the output at idle. Some significant negative effects are appearing at low load due to the high switching frequency: skin effect and proximity effect. These effects are negate the whole idea of high-performance transformations. That's why this topology is also a poor choice in automotive application.

2.3. LLC resonance circuit

There is LLC resonance circuit in figure 8.
LLC resonant Converter have been proposed to overcome the limitation of series resonant converters. It is a modification of the serial LC resonant Converter implemented by placing a shunt inductor parallel to the primary winding of the transformer, as shown in figure 8. This topology has not received much attention when it was first presented. This is because of the circulating current increasing in the primary winding with a shunt inductor. It can not be beneficial to the circuit operation. However, it can be very effective in improving the efficiency for the use of high input voltage, where the switching losses dominate much more than the loss of conductivity. In the most practical design, this shunt inductor is realizing with the magnetizing inductance of the transformer. Diagram of the LLC resonant Converter looks the same as a serial resonant LLC Converter. The value of magnetizing inductance Lm is the only Difference from the other scheme. The series resonant Converter’s magnetizing inductance is much larger than the resonant inductance (Lr) serial LC resonant circuit. But in the LLC resonant Converter scheme the inductance (Lr) is just 3 ~ 8 times larger, which is usually implemented by introducing an air gap in the transformer as leakage inductance. Minimization of magnetic components and their integration in the transformer is a huge advantage of an LLC Converter over other topologies.

Figure 10 illustrates the work of the LLC-Converter. The drain current $I_{ds2}$ takes negative values, while it flows through the inverse diode of MOSFET and the voltage drop is practically zero (drop voltage on the open diode).

The drain current takes negative values, while it flows through the inverse diode of MOSFET and the voltage drop is practically zero (the voltage drop across the open diode).

At this moment the MOSFET opens and the switching losses are significantly reduced, so the efficiency of the Converter reaches 95%, which is a very good value. Besides, it stands to mention that form voltage is very close to the sine wave, thereby reducing the level of interference.

LLC topology is the best one for the implementation of advanced energy efficient voltage Converter.

3. Conclusions
Converters with sinusoidal current waveform have a number of advantages compared to converters with rectangular current. The lack of large values of $di/dt$ and $dv/dt$ simplifies the filtering and control of electromagnetic interference. Switching losses are lower, as current at the time of switching is zero. The recovery losses of rectifier are low, because of small magnitude $di/dt$. The load on all components is less, which gives improved reliability of the device.

The maximum operating frequency of the switching converters is mainly determined by the magnetic components. Achievement of the required performance is an easier task in the case of the resonant Converter, because the transformer passes only a sine wave at the fundamental frequency. Converters square wave needs to pass the harmonics and the fundamental frequency. Therefore resonant converter require a transformer with a wider range of frequencies to avoid unacceptable losses or distortions. [3]

Thus, resonant converters can achieve the advantages in the high-frequency operation without compromising cost, efficiency, reliability and electromagnetic compatibility. LLC scheme topology was considered as the best topology.

References
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