

Efficiency Optimization of the High-Power Isolated DC/DC Converters through THD and Losses Reduction in Isolation Transformers

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Abstract. This paper describes a method of improving efficiency of the high-power transformer-isolated DC/DC converters by means of proper selection of an inverter switch duty cycle. The paper revises old suggestions and recommendations for choosing the maximal duty cycle value on the basis of physical limits imposed by new solid-state devices. The resulting improved efficiency of the converter is described considering losses in separate energy conversion stages.

Keywords

DC/DC converters, efficiency, isolation transformer, inverter.

1. Introduction

High-power transformer-isolated DC/DC converters have a wide scope of applications, e.g. in auxiliary power supplies (APS) of the rolling stock. The continuous failure-free operation of the APS must be guaranteed within the following limits of the supply voltage:

$$0.67U_{in,nom} \leq U_{in} \leq 1.3U_{in,nom}, \quad (1)$$

where $U_{in,nom}$ is the nominal value of the traction catenary. In the rolling stock applications, the output voltage at the rated load should not change over the full range of the input voltage fluctuations.

2. Inverter-Transformer Assembly: Design and Operation

The operation of DC/DC converter must be precisely coordinated to achieve higher efficiency and flexibility of the whole converter. For the described application, the half-bridge isolated DC/DC converter topology (Fig. 1) suits very well: despite relative simplicity, it can provide galvanically isolated output voltage with good regulation properties and with reduced voltage stress on the primary switching devices. General specifications are presented in Table I.

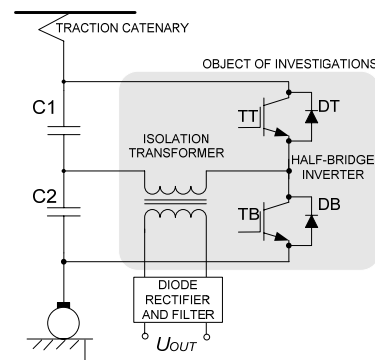


Fig. 1. Simplified scheme of the converter for the onboard APS

TABLE I. - Technical Specifications of the Converter

Continuous minimal input voltage $U_{in,min}$, VDC	2000
Continuous maximal input voltage $U_{in,max}$, VDC	3900
Nominal input voltage $U_{in,nom}$, VDC	3000
Switching frequency f_{sw} , kHz	1
Converter output voltage U_O , VDC	350
Desired output power P_O , kW	50

The idea of the control of half-bridge converter operating under the large input voltage swing is to maintain the constant volt-seconds applied to the transformer primary winding. In other words, the relation $U_{in}D$ (where U_{in} is the input voltage and $D=t_{on}/T_{sw}$ is the transistor duty cycle) should be constant in all the operating points of the converter. The duty cycle of the inverter switch should change inversely proportional to U_{in} to maintain a constant output voltage, U_O .

The operation of the inverter-transformer assembly should be analyzed in two most demanding operating points: at minimum input voltage, where the switch duty cycle is maximal (D_{max}) and at maximum input voltage, where the duty cycle is minimal (D_{min}). Another important operating point is the nominal operating point corresponding to the nominal operating voltage.

3. Selection of the Duty Cycle Variation Range

The selection procedure of the duty cycle variation range begins from the definition of the maximum switch duty cycle. According to conservative design practice several unified values of the maximum switch duty cycle, such as $D_{max}=0.45$ or even $D_{max}=0.4$, are used. This is done mostly to prevent a short circuit. The conservative selection procedure based on predefined D_{max} values is not always useful because it limits the flexibility and even can reduce the efficiency of the inverter-transformer assembly. The selection of D_{max} should be individually performed in respect to the specific properties of the converter.

To improve the efficiency and flexibility of the DC/DC converters, the authors propose to shift the maximum switch duty cycle D_{max} towards the limiting value D_{lim} , which depends on the interlock delay time between switching on and off the opposite arm transistors. The discussed converter based on 6.5 kV 200 A IGBTs with dedicated drivers has the interlock delay time about $t_{IDT}=9$ us, resulting in the absolute maximum duty cycle $D_{lim}=0.49$.

4. Impact of Different Duty Cycle Variation Ranges on the Efficiency of the Inverter-Transformer Assembly

To verify how the selection of the duty cycle range can affect the efficiency of the inverter-transformer assembly, a series of experiments were performed (Table II). The first two ranges *A* and *B* were selected upon the standard procedure with maximum duty cycles of 0.4 and 0.45. The third duty cycle variation range *C* was based on the proposed design improvement procedure.

TABLE II. - Duty Cycle Variation Ranges Used in the Analysis

CASE STUDY	D_{max} ($U_{in,max}=2000$ V)	D_{nom} ($U_{in,nom}=3000$ V)	D_{min} ($U_{in,max}=3900$ V)
A	0.4	0.27	0.21
B	0.45	0.3	0.23
C	0.49	0.33	0.25

A. Operation of a Half-Bridge Inverter

With the duty cycle being shifted towards maximum, the rms voltage applied to the transformer's primary winding will be increased due to the longer conduction time. For the same transferred power, the rms value of the primary current should proportionally decrease, thus having a positive influence on the inverter losses.

The analysis shows that on an increase of the switch duty cycle at the maximal input voltage by 22.5%, the total losses of the half-bridge inverter could be reduced by 8.1%. The proportional increase of the duty cycle insures a 7.5% and 6.3% loss reduction at the nominal and minimal input voltages, respectively. Although the efficiency of the inverter is increased only by some fractions of percent, the cooling effort could be reduced, thus resulting in a more space-saving design.

B. Operation of the Isolation Transformer

Three different isolation transformers were designed for the cases *A*, *B* and *C*. Each transformer operation was analyzed in three operating points – at U_{min} , U_{nom} and U_{max} with the corresponding D_{min} , D_{nom} and D_{max} . The research shows that the total power losses decrease from case *A* to case *C*. As a result, the isolation transformers designed for the higher maximal duty cycle value demonstrate higher efficiency at any operational voltage and duty cycle (Fig. 2).

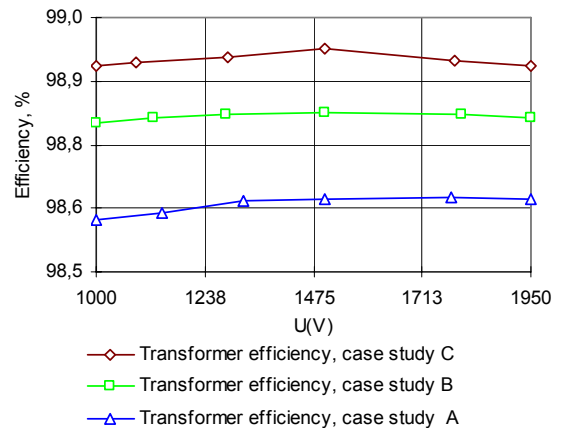


Fig. 2. Comparison of the efficiency of different isolation transformer designs for the same operating voltage range

5. Conclusions

In this paper, efficiency improvements of the high-voltage isolated DC/DC converter by means of the improved selection of the variation range of the duty cycle of the inverter switch are discussed. A new extended approach of the inverter duty cycle selection is proposed. To verify the proposals, the efficiency of the inverter and isolation transformer was estimated and compared for three different duty cycle variation ranges.

It was found that the new method provides an efficiency rise of the high-voltage half-bridge isolated DC/DC converter. In the case of the investigated rolling stock auxiliary power supply with the rated power of 50 kW even moderate efficiency improvement in 1% will be followed by the 0.5 kW...1 kW smaller heat dissipation, thus resulting in a reduced cooling effort and, therefore, higher power density of the designed converter.

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