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Direct Parallel Connection of DC-DC Power Circuits with Galvanic Isolation

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Professional paper

A DC-DC converter made of two identical IGBT full bridge power circuits is built. The two circuits are directly connected in parallel and driven with only one control circuit originally built for one IGBT bridge. One signal drives two corresponding IGBTs in parallel bridges without any additional circuits for current sharing. The main causes of possible current unbalance were identified by simulation. The difference among transformer leakage inductances has, by far, the most significant influence on current sharing between two circuits. This was confirmed by measurements. It is concluded that transformer tolerances regarding leakage inductances that can be achieved in normal series production will ensure an acceptable current sharing.

Key words: DC power supplies, converter control, parallel converter connection

1 INTRODUCTION

There are many reasons for paralleling power circuits or converters. Current/power ratings of available components (power semiconductors, transformer core) may be too small to handle the needed power. The only solution is to parallel components, parts of a circuit or whole converters. Another approach where parallel converters are needed are modular power systems. Different power levels and input/output specifications are configured with parallel and/or series connection of one type of modular power supply [1]. The need for redundant and reliable operation is also a reason for parallel combinations of circuits [2].

In this case a power converter with two parallel power circuits is built mainly because of dissipation limitations. The starting point for the new converter was a simple 4.5 kW DC-DC power converter with hard switching working at 20 kHz. The converter is described in [3], where it is concluded that for the specific application the power of the converter could be raised up to 6 kW. For the new converter, output power of 12 kW was specified. Simple bridge circuit with four IGBTs as used in the 4.5 kW converter was not an envisageable solution because of high loses in IGBT modules. Consequently, junction temperature will be too high for reliable operation. Not only the absolute value, but also the temperature swing have to be taken in consideration due to frequent start/stop sequences. Soft switching techniques enable 20 kHz operation of IGBTs even at much higher power levels [4], but in our case this was not an option because there was no time available for additional investigations. The simplest solution was to parallel two power circuits of 6 kW with one existing control circuit without any additional circuits for current sharing. A current imbalance was likely to occur. An analysis described in the paper was carried out by simulation and measurement to see if this imbalance is acceptable. Design guidelines and measures for minimising imbalance were derived from the presented analysis.

2 CONVERTER CHARACTERISTICS AND CIRCUIT DESCRIPTION

The converter is a part of a converter system for auxiliary supply for trams. Input voltage is a catenary DC voltage 400 V to 750 V. Other main design specification are:

- nominal output voltage is 290 V DC, regulated
- nominal output power is 12 kW,
- safety galvanic input-output separation,
- 20 kHz working frequency, hard switching,
- outside mounting (tram roof),
- natural cooling preferable.

Figure 1 shows the converter structure with outlined regulation and drive signals. As shown, the converter power circuit consists of two full bridge converters in parallel. Input filter inductance could be split in two inductors, but in this case it is realised as one inductor for the reason of simpler mechanical design.

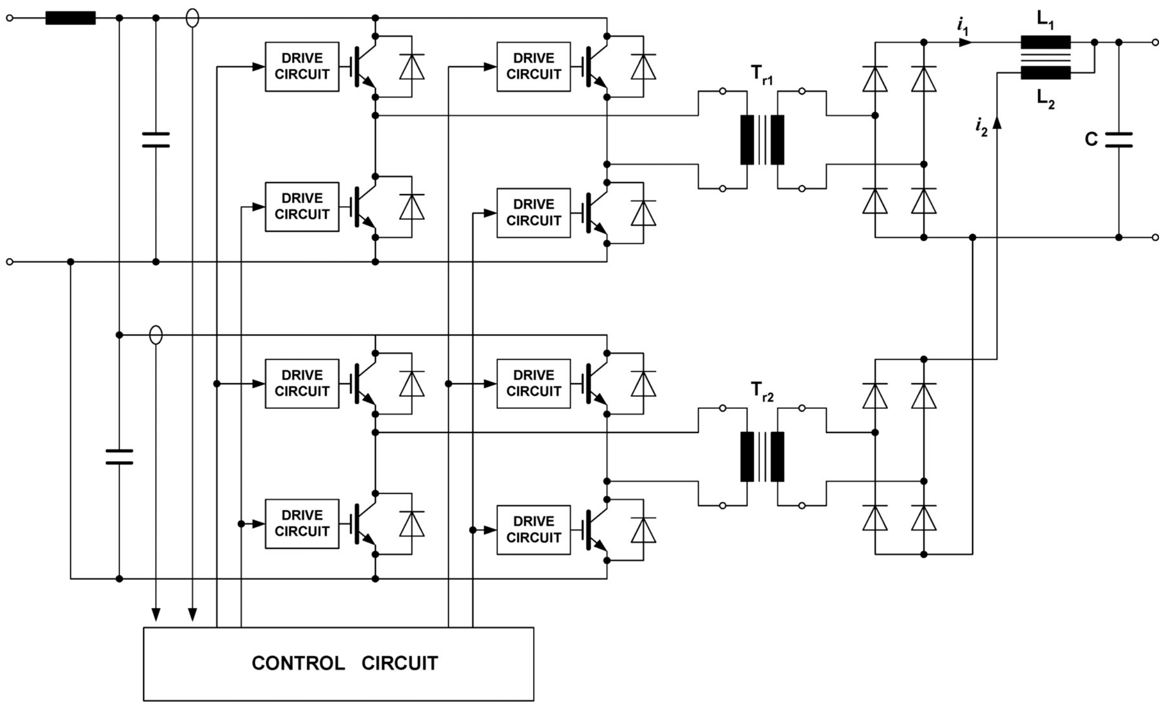

Fig. 1 Converter structure

For regulating the output voltage, the existing control circuit developed for one bridge converter is used with some minor changes. Current signals at input of each bridge are summed to form one current signal for current mode control. One drive signal, previously used at the input of one gate drive circuit is now fed to the input of two gate drive circuits used for driving two corresponding IGBTs, each in its power circuit.

Since current waveforms of both output inductors are practically equal, they can be wound on one core, preferably of the same type as the one used for the transformers, simplifying thus the mechanical design.

If compared with one bridge converter, the reliability of this solution and its disposability, in spite of a greater number of drive circuits, are both higher because it is possible to operate only one half of the converter if the other half fails (except for short circuit in output rectifiers). This can be favourable in applications where the load can be supplied with half the power, only for critical functions.

3 THEORETICAL CONSIDERATIONS

Ideally, output current will be shared equally between two converters if they are identical. If one or more parameters are not equal, imbalance of converter currents will occur. In start, it is supposed that main parameters that have influence on current sharing are:

- dead time from the input of the drive circuit to the IGBT output,
- transformer impedances (magnetizing currents, losses, leakage inductances),
- voltage drops (resistive, collector-emitter saturation voltage u_{CEsat}, diode forward voltage V_F),
- inductances of output inductors.

3.1 Transformer leakage inductance

If only transformer leakage inductance L_{lk} is taken in consideration and with 1:1 transformer ratio, the converter with ideal switches and diodes can be represented as on scheme in Figure 2. The switches are driven with a PWM signal of constant frequency, and the converter operates in continuous current mode.

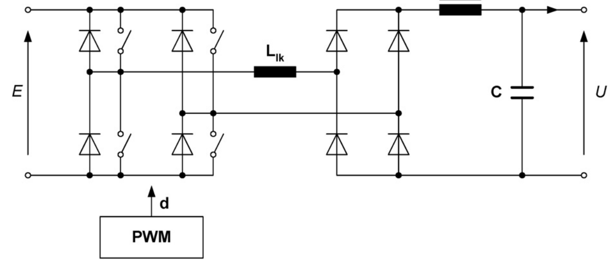

Fig. 2 Simplified schematic of the converter with transformer leakage inductance L_{lk} and 1:1 transformer ratio

Output voltage can be expressed with the well known basic relation as

$$U = E d_{ef} \tag{1}$$

where d_{ef} is the effective duty cycle at the output of the diode rectifier:

$$d_{ef} = d - T_k f. \tag{2}$$

- d is the duty cycle imposed by the control circuits at the input switch bridge
- T_k is the commutation time needed for the input current to raise from zero to the value of the output inductor current at the beginning of the on-period
- f is the frequency of the voltage at the output of the diode bridge.

During diode commutation time the voltage at the input of the LC filter is zero, and therefore the value $T_k f$ is subtracted from the value of the duty cycle determined by the PWM circuit. T_k can be calculated according Figure 2 as

$$T_k = L_{lk} \frac{I + \frac{\Delta I}{2}}{E}. \tag{3}$$

ΔI is the value of the current swing in the output filter inductor in steady-state operation. Other quantities are defined in Figure 2. By combining (1), (2) and (3):

$$U = Ed - \left(I + \frac{\Delta I}{2} \right) L_{lk} f. \tag{4}$$

In first approximation, the value $L_{lk}f$ acts as internal impedance in series with an ideal voltage source.

In this specific application L_{lk} is typically 10 μH, $f = 40$ kHz, what gives $L_{lk}f = 0.4\ \Omega$. Equivalent transformer resistance calculated as $R_{Cu} = P_{Cu} / I_p^2$ (where P_{Cu} are winding loses, and I_p the RMS primary current) summed with filter inductor resistance transformed to the primary side for this specific converter is typically 60 mΩ (40 mW for transformer and 20 mW for inductor) which is les by one order of magnitude compared with $L_{lk}f$. We can expect that the transformer leakage inductance will have the greatest influence on current sharing.

3.2 Voltage drops and dead time

The first term in (4) will vary in a real case from converter to converter due to variations in current independent voltage drops (V_F and u_{CEsat}) that are subtracted from the value of input voltage E and due to variations of duty cycle d. Small inequalities in duty cycles are possible since the dead times from one to another drive circuit will vary. The influence of these factors can be calculated as follows.

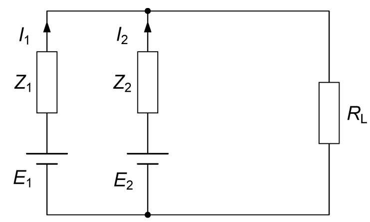

Fig. 3 Linear representation of two parallel converters

A simple linear representation of two parallel converters is given in Figure 3. If $Z_1 = Z_2 = Z$ (to take into account only the difference in values of voltage sources), from Figure 3 we get for current distribution:

$$\frac{I_1}{I_2} = \frac{E_1 - E_2}{I_2 Z + 1}. \tag{5}$$

The voltage difference $(E_1 - E_2)$ must be kept small enough compared to the internal impedance voltage drop in order to minimise its influence.

It is expected that the current distribution will be temperature stable. The major factors that influence current distribution are temperature independent (leakage inductance) or have a positive temperature coefficient (copper resistance, IGBT saturation voltage). Only the diode forward voltage drop has a negative temperature coefficient, but compared with other factors combined together its influence can be considered small enough [5, 6].

4 SIMULATION AND TEST RESULTS

The converter in Figure 1 is simulated using Simplorer simulation tool. Output filter inductors are simulated as two separated inductors L_1 and L_2. IGBTs are simulated as ideal switches with diode-like characteristic during conduction. The transformer and inductor models include losses, magnetizing and leakage inductances. All parameters are set (Table 1) as calculated and measured on the specific converter. For simulation the nominal working point is chosen. Each IGBT bridge is driven with fixed, independent PWM signal adjusted to get the nominal output voltage with nominal output current. As simulation output, the DC components I_1, I_2 of the two output filter inductors are chosen. In the ideal case two converters are equal, with the total output current $I_1 + I_2 = 20 + 20 = 40$ A. Subsequent simulations were carried by varying only one of the parameters in lower converter (with current I_2) and adjusting d, so that the total output current is kept at 40 A. Variations were set as expected in practice or somewhat exaggerated, to see clearly the resulting difference among currents. Simulation results are summarised in Table 1.

Table 1 **Simulation results: current sharing for converter on Figure 1**

Simulation No.	Parameter	Starting value	Value varied (only in converter 2)	Currents after parameter variation	
				I_1, A	I_2, A
1	IGBT bridge u_{Cesat} @ $I_C = 20$ A, V	2.0	2.5	21.0	19.0
2	Output diode bridge V_F, @ $I_F = 20$ A, V	1.5	2.0	20.9	19.1
3	Transformer core loses, W Transformer winding loses, W	12 12	16 16	20.2	19.8
4	Transformer leakage inductance from primary side L_{lk}, μH	5	7	22.45	17.55
5	Output filter inductance L, μH	660	600	20.1	19.9
6	Transformer magnetizing inductance L_μ, mH	5	2.5	20.15	19.85
7	Duty cycle d	12.5/25	12.4/25	23.0	17.0

Waveforms of output filter inductor currents i_1 and i_2 from simulation No. 4 are given in Figure 4. Measurements were carried on the first lot of eight transformers that were built in the first four manufactured 12 kW converters. An inductance on primary side with short-circuited secondary is measured. A value of 6 μH ± 0.15 μH is measured for all transformers.

Converters were built without any extra measures (components matching) regarding current distribution. Three of four converters have well distributed currents within ±2 %. One converter shows a difference between output filter inductor currents i_1 and i_2. In Figure 5 are the measured waveforms of output filter inductor currents i_1 and i_2 for total output current of 36.1 A.

The DC components were $I_1 = 18.9$ A and $I_2 = 17.2$ A. The temperature difference in corresponding transformer windings was also measured. For

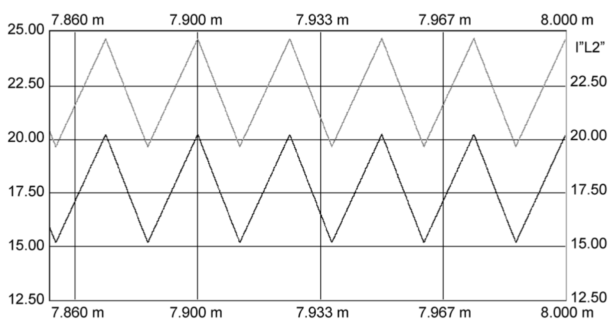

Fig. 4 Simulated current waveforms of output filter inductors in parallel converters with different transformer leakage inductances (simulation No. 4). Vertical scale in ampers, horizontal scale in miliseconds

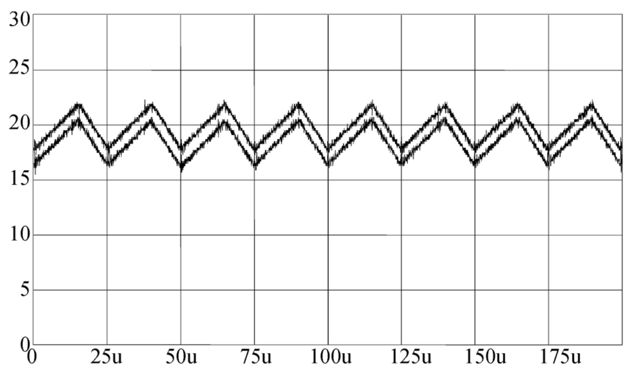

Fig. 5 Measured waveforms of output filter inductor currents in case of imbalance

transformer Tr_1 with higher current, the winding temperature above the ambient $\Delta T_1 = 34$ °C, and for the other $\Delta T_2 = 30$ °C. This is considered still acceptable.

The cause of imbalance in this case was explained by the difference in length of transformer wiring cables for transformers Tr_1 and Tr_2, since the converter in question was not made with the same mechanical layout as the other three. For qualitative evaluation, an inductance of 2.2 μH made of 5 turns of connecting cable was inserted in series with primary of the transformer with higher current. This resulted again in current imbalance, but with practically reversed values of I_1 and I_2. $I_1 = 17.6$ A and $I_2 = 18.5$ A, compared to the previous $I_1 = 18.9$ A and $I_2 = 17.2$ A. This means that with an inductance around 1 μH a good current balance could be achieved.

5 CONCLUSION

The best way to maintain current distribution among paralleled converters under control is to have transformers with leakage inductances L_{lk} high enough, so that the voltage drop defined with $L_{lk}f$ is dominant compared to other parasitic voltage drops. The leakage inductance is time and temperature stable. Transformers are easily manufactured with tight tolerances of leakage inductances. The negative side is that the voltage stress of output diodes is higher. Also, the layout of paralleled circuits has to be equal and with the same cooling conditions, what is, generally, easily ensured.

The proposed solution is not presented as the optimum one, but only as a possibility to build a converter with n-times higher transferred power in a simple way with available control circuitry.

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Izravni paralelni spoj energetskih krugova istosmjernih napajača s galvanskim odvajanjem. Izrađen je istosmjerni napajač sastavljen od dva istovjetna IGBT pretvarača u punom mosnom spoju. Energetski krugovi oba pretvarača su spojeni izravno u paralelu, a upravljaju se postojećim upravljačkim sklopovima predviđenim prvobitno za jedan pretvarač. Jedan upravljački signal se vodi istovremeno na dvije odgovarajuće IGBT-sklopke, u paralelnim mostovima. Nisu predviđeni nikakvi dodatni sklopovi koji bi ujednačavali raspodjelu struja. Simulacijom su određeni osnovni uzroci moguće neravnomjerne raspodjele struja po pretvaračima. Ustanovljeno je da razlika u rasipnim induktivitetima transformatora osnovni uzrok neravnomjerne raspodjele struja. Ovo je potvrđeno mjerenjima. Zaključeno je da su tolerancije rasipnih induktiviteta koje se postižu u redovnoj proizvodnji transformatora takve da je osigurana prihvatljiva raspodjela struja.

Ključne riječi: istosmjerni napajači, upravljanje pretvaračima, paralelno spajanje pretvarača

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