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Zero voltage switching converter for magnetic transfer of energy to movable systems

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Abstract

A power converter for energy transfer to movable systems with low switching losses, voltage clamping and the ability to recover energy is proposed. Design aspects of the converter and the power transfer system are described. The static and transient behaviour of the converter are shown.

Keywords: Magnetic power transfer, Zero voltage switching converters

Summary

1 Introduction

A common problem of electrical driven linear moving devices is to deliver the required energy.
Conventinal systems use on board batteries, brushes or cables (in short distance systems).
These systems have different disadvantages, like faulty mechanical contact, malfunction of cable damage, dangerous hazards caused by sparks or the weight of an on board battery.
A new solution is the use of magnetic energy transfer which is an interesting alternative especially for systems with a fixed roadway.
Such a transfer system is proposed in [1] and [2]. Based on a modified version of this system a secondary sided converter with voltage clamping and soft switching is proposed in this paper. The converter feeds a dc voltage-link. Its main advantages are low switching losses and a simple structure.

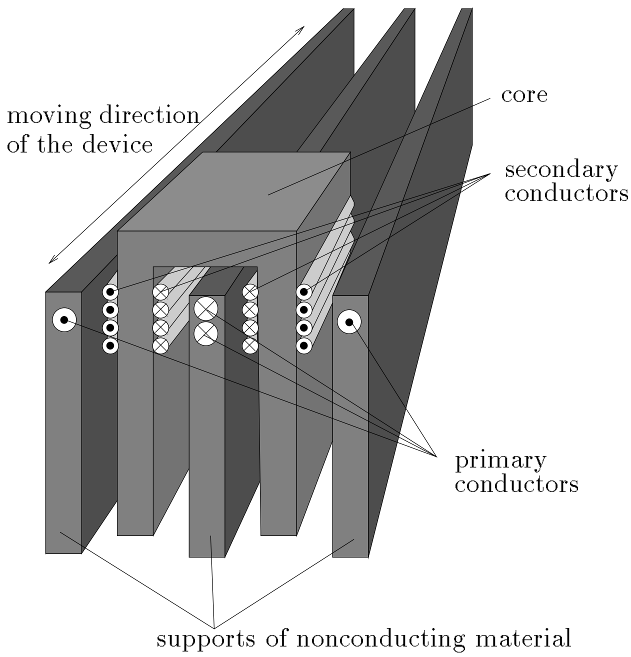

Figure 1: Connectorless power transmission

2 Structure and design of connectorless power transfer

The structure of a connectorless power transmission is shown in figure 1. The primary pathway consists of two long conductor loops in the range of some hundred meters. A reduction of electromagnetic emission is achieved by the use of two conductor loops whose electromagnetic fields compensate each other in a short distance besides the pathway. To reduce eddy currents the primary conductor loops are inserted in nonconducting supports.

The secondary side moving device and the primary pathway are separated by an air gap in the range of millimetres to centimetres, which is necessary because of the mechanical tolerance of the moving device. So a sufficient inductive coupling can only be ensured by a wide magnetic cross-sectional area. To reduce the effective air gap it is possible to form the support in the middle out of ferrite.
The secondary side moving device is inductively coupled with the primary pathway by the u-core shown in figure 1. To reduce secondary leakage inductance the pimary and secondary sided conductors are placed in

the same level. The secondary leakage inductance of the transformer is caused to a great extent by end leakage, so the u-core has to be designed long and narrow. Finite-element calculation gave a secondary leakage inductance of approximately 5% of the magnetizing inductance for the used u-core.

In order to reduce the size of the u-core and to avoid audible emissions caused by the converters the system is driven with a frequency of 25 kHz.

If there is more than one moving device on the same pathway, the secondary sided systems work as a series connection. To avoid interference between the secondary sided systems the primary current has to be impressed.

To minimize the reactive power which has to be delivered by the primary converter the inductance of the primary conductors has to be compensated by capacitors connected in series with the line sections (see [2]).

3 Demands on a secondary sided converter

The secondary sided converter has to fulfill the following requirements:

- In case of no-load operation of a moving device its converter must have a switching mode which shorts the magnetizing inductance in such a way that other moving devices on the same pathway are not affected.
- In case of fault high currents or voltages which can damage the system must be avoided.
- A good efficiency of the whole system is mandatory. Therefore the ability to feed back energy from the moving device is very useful.
- The converter should work with a good power factor to reduce reactive power which has to be transmitted.

4 Secondary sided converter with voltage clamping and soft switching

In figure 2 the circiut of the secondary sided converter is shown which feeds a dc load (voltage V_g, $C_g \gg C_k$).

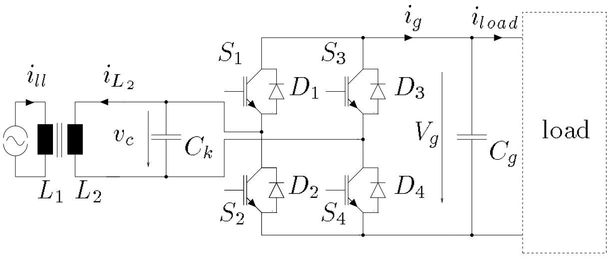

Figure 2: Converter with voltage clamping

The primary system can be described as a current source i_{ll}. L_1 and L_2 represent the primary and secondary magnetizing inductance. The secondary leakage inductance is neglected in the figure in order to simplify the following description. The IGBTs S_1 to S_4 and diodes D_1 to D_4 represent the converter.

The operation of the converter is illustrated in the following figure.

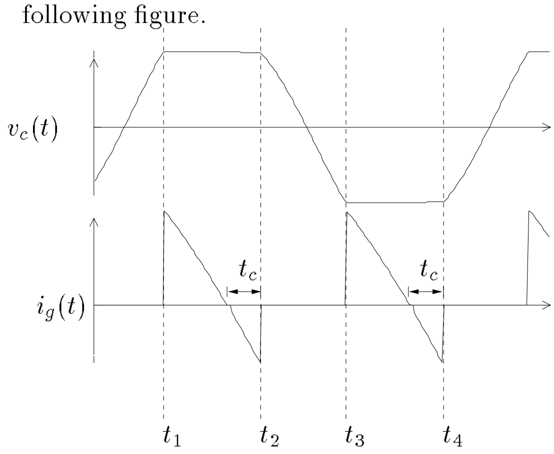

Figure 3: Operation of the converter

As long as the absolute value of the voltage v_c is less then V_g the parallel circuit consisting of C_k and L_2 is fed by the current $i_{ll} \cdot \sqrt{L_1/L_2}$. If v_c reaches V_g (see t_1 in figure 3) the current through the capacitor C_k commutates to the diodes D_1 and D_4 connected anti-parallel to the IGBTs S_1 and S_4. The voltage v_c is now clamped and energy is transferred to the secondary sided moving device. During the conduction time of the diodes D_1 and D_4 it is possible to switch on the IGBTs S_1 and S_4 under zero voltage condition. The current i_g between t_1 and t_2 is given by:

$$i_g = i_{ll}(t) \cdot \sqrt{\frac{L_1}{L_2}} - \frac{1}{L_2} \cdot V_g \cdot (t - t_1) - i_{L_2}(t_1)$$

When the current i_g crosses zero the IGBTs S_1 and S_4 start conducting and energy is transferred back from the moving device to the primary pathway. Because of the parallel connected capacitor C_k the IGBTs are switched off softly at t_2. So low switching losses and a good efficiency are expected. The area between t_3 to t_4 shows the vice versa behaviour if v_c reaches $-V_g$. By increasing the conduction time t_c of the IGBTs energy recovery is possible. The operation range of a converter with

$$\hat{i}_{ll} = 28.28A$$
$$L_1 = 4\mu H$$
$$L_2 = 100\mu H$$
$$C_k = 0.35\mu F$$

is shown in figure 4.

No-load operation is possible by closing the IGBTs S_1 and S_3 or the IGBTs S_2 and S_4. In this case the resonant circuit L_2 und C_k is shorted and neither reactive nor active power is transmitted.

5 Design and control of the converter

A high value of the magnetizing inductance reduces the necessary magnetizing current but is limited by the size of the u-core and the air gap.
The parallel capacitance C_k has to fulfill the following equation to ensure that the voltage V_c reaches V_g:

$$\left| \hat{i}_{ll} \cdot \sqrt{\frac{L_1}{L_2}} \cdot \frac{1}{\frac{1}{j \cdot \omega \cdot L_2} + j \cdot \omega \cdot C_k} \right| \geq V_g$$

To enhance the power factor of the converter the parallel capacitance can be chosen smaller than $1/(\omega^2 \cdot L_2)$ because the converter generates reactive power.
The transferred energy can be controlled by choosing the integral of the current through the IGBTs q_{sw} as actuating variable (see figure 4), which is used to set the switching instant.

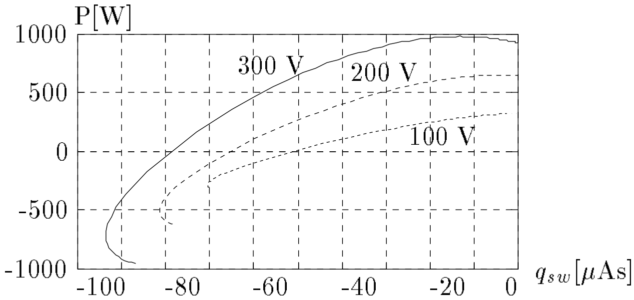

Figure 4: Transferred power as a function of the integral of the IGBT current with different values of V_g (calculated results)

It can be seen that it is necessary to limit the power range to ensure that every current integral q_{sw} is assigned to one value of transmitted power. With $V_g = 300V$ power in the range of -750 W to 960 W can be transferred.
The transferred energy during a half cycle can be determined by the integration of the complete input current i_g. The transfer function of the mean value of i_g to the integral of the current through the switches or the switching instant, respectively, is similar to a first-order time delay. This can be seen in figure 5.

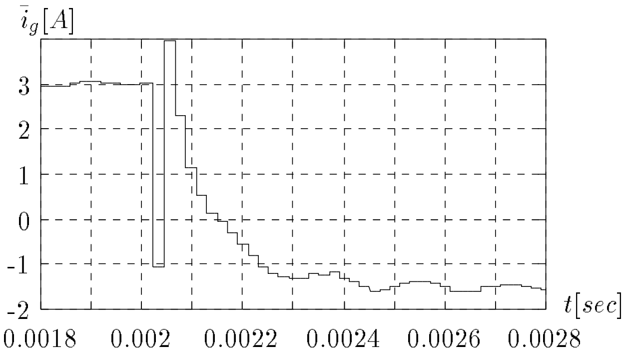

Figure 5: Open loop answer of the mean value of $i_g(t)$ to a step of switching instant. The mean value of the IGBT current is reduced at t=2msec. Energy conversion starts at 2.15msec.

If the value of V_g is assumed to be constant during a half cycle the control of the mean value of i_g, leads to a control of the transferred energy. It can be done by using an I-controller F_R and the inverse of the characteristics shown in figure 4. They depend on the voltage V_g. It is possible to calculate these curves offline and manipulate them to limit the power range. Using these inverse characteristic curves the open-loop gain is kept constant.
The structure of the control is shown in figure 6.

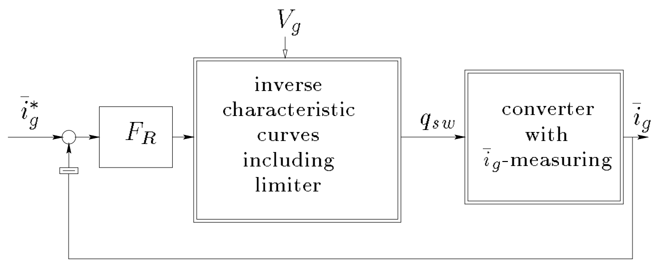

Figure 6: Control of the amount of transferred energy by controlling the mean value of i_g

6 Simulation results

The dynamic behaviour of the converter with the control of the mean value of i_g at a fixed voltage V_g of 300 V is shown in figure 7.

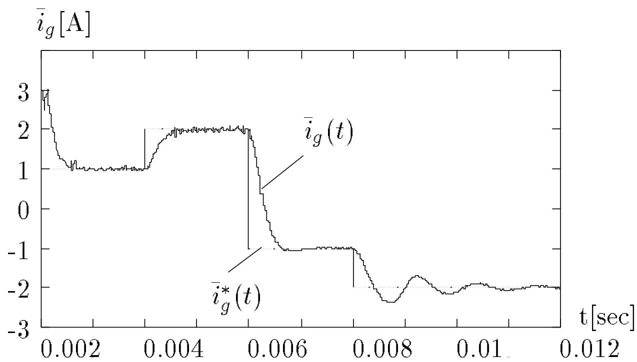

Figure 7: Setpoint value $\bar{i}_g^*(t)$ and actual value $\bar{i}_g(t)$ of the mean value of i_g

Further simulated and experimental results and a more detailed analysis of the dynamic behaviour will be shown in the final paper.

References

[1] A non-contact power distribution system. patent no. WO 93/23908, November 1993.

[2] A primary inductive pathway. patent no. WO 93/23909, November 1993.