A METHOD TO OPTIMIZE THE SIZE OF THE TRANSFORMER CORE FOR MAGNETIC POWER TRANSFER TO LINEAR MOVING DEVICES

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Abstract. In this paper a system for non-contact power transfer to linear moving devices is described. It has the ability to feed several independent moving devices. The primary pathway consists of two long conductor loops, which carry a sinusoidal current. The moving device is magnetically coupled with the primary pathway by a u-core made of ferrite. One aim of the research is to minimize the size of this u-core for a given amount of power which has to be transferred. To reduce the size of the u-core and to deliver the required magnetizing current for the u-core a capacitor is connected in parallel. Based on the description of two different types of secondary-sided converters, one feeding a dc voltage link, the other with a dc current link a new method to optimize this parallel circuit for a given power is proposed. A comparison of the two above mentioned converter-types concerning the parameters of the resonant circuit at a primary current with a frequency of 25 kHz is presented.

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INTRODUCTION

This paper deals with the supply of energy to electrically driven linear moving devices. Conventional systems use on board batteries, brushes or cables (in short distance systems).

Such systems have different disadvantages as faulty mechanical contact, malfunction by cable damage, dangerous hazards caused by sparks, or the weight of an on board battery.

A new approach is the use of magnetic energy transfer which is an interesting alternative especially for systems with a fixed roadway.

A few transfer systems are proposed until now ([3],[4]). A modified version of this transfer systems is described in the following section. Based on this transfer system two secondary-sided converter-types will be presented and finally a method to optimize the size of the transformer core for a given power is proposed.

CONTACTLESS POWER TRANSFER SYSTEM

The structure of a contactless 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 and losses the primary conductor loops are made of litz wire and are inserted in nonconducting supports.
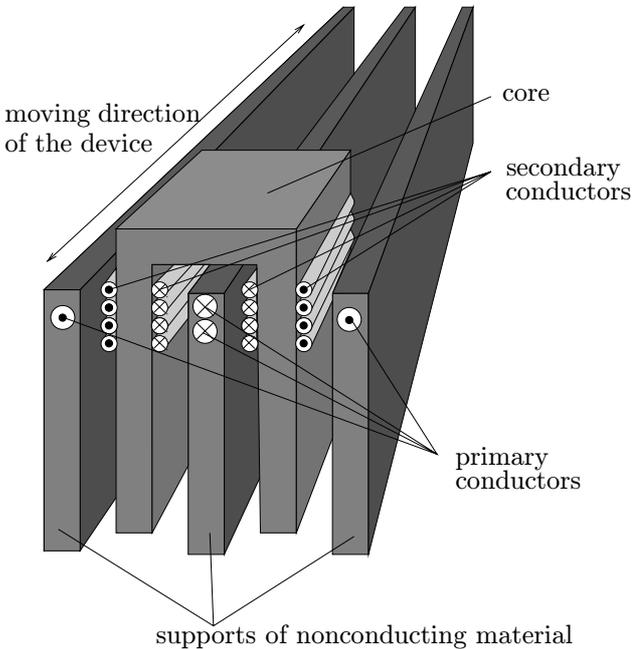

Figure 1: Contactless power transmission

The moving device and the primary pathway are separated by an air gap in the range of millimetres to centimetres according to the necessary mechanical tolerance of the moving device. So a sufficient magnetic coupling can only be ensured by a wide magnetic cross-sectional area. To reduce the effective air gap it is also possible to realize the middle support using ferrite.

The moving device is inductively coupled with the primary pathway by the u-core shown in figure 1. To guarantee a sufficient magnetic coupling and to reduce the secondary leakage inductance of the transformer, which is caused to a

great extent by end leakage, the u-core has to be designed long and narrow.

In the following descriptions L_1 and L_2 represent the primary and secondary magnetizing inductance. The secondary leakage inductance is neglected in order to simplify the equations. To reduce the size of the u-core and to deliver the required magnetizing current for the u-core a capacitor is connected in parallel to L_2.

The primary system can be described as a current source i_{ll}.

$$i_{ll}(t) = \hat{i}_{ll} \cdot \sin(\omega \cdot t + \varphi) \tag{1}$$

In the following descriptions $i_{ll2} = \sqrt{L_1/L_2} \cdot i_{ll} = 1/N_2 \cdot i_{ll}$ is used.

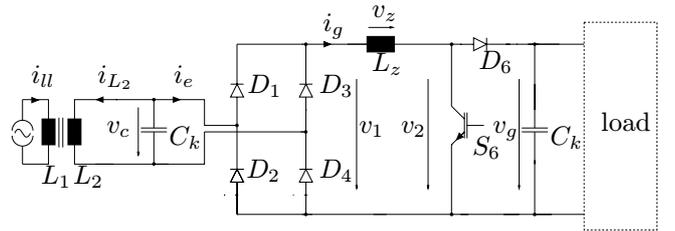## SECONDARY-SIDED CONVERTER WITH A DC CURRENT LINK

Figure 2: Converter with dc current link

Figure 2 shows a secondary-sided converter with a dc current link [1, 5]. The converter consists of a passive bridge and a boost converter. The operation of the converter is shown in figure 3.
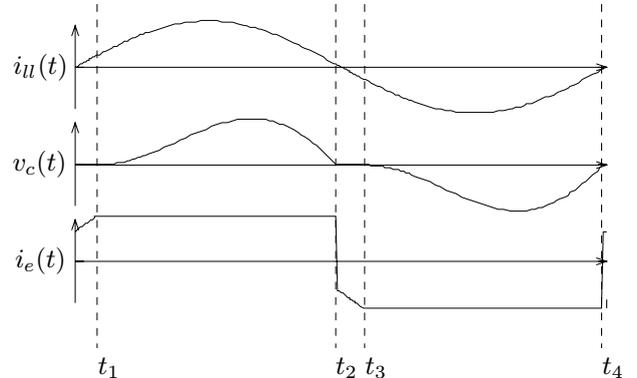

Figure 3: Operation of the converter

If i_e is lower than i_g the capacitor C_k is shorted. At t_1 i_e reaches i_g. Energy is transferred to the moving device until t_2. The amount of transferred energy can be controlled by v_2, which is controlled by the duty ratio of the boost converter. Assuming steady-state operation the mean-value of v_1 is equal to that of v_2.

$$\frac{2}{T} \cdot \int_{t_1}^{t_3} v_1(t)\, dt = \frac{2}{T} \cdot \int_{t_1}^{t_3} |v_c(t)|\, dt = \frac{2}{T} \cdot \int_{t_1}^{t_3} v_2(t)\, dt \tag{2}$$

The following differential equations describe the operation of the converter:

$$v_c(t) = \frac{1}{C_k} \cdot \int (-i_e(t) - i_{L_2}(t))\, dt \tag{3}$$

$$i_{L_2}(t) = \frac{1}{L_2} \cdot \int v_c(t)\, dt - i_{ll2}(t) \tag{4}$$

The mathematical description of the converter results of the equations (1)-(4) and the smooth transition of i_{L_2} and v_c at t_1 and t_2. A detailed analysis of the mathematical description will be shown in the final paper.

SECONDARY-SIDED CONVERTER FEEDING A DC VOLTAGE LINK

Figure 4 shows the circuit of the secondary-sided converter [2] which feeds a dc voltage link (voltage v_g, $C_g \gg C_k$).
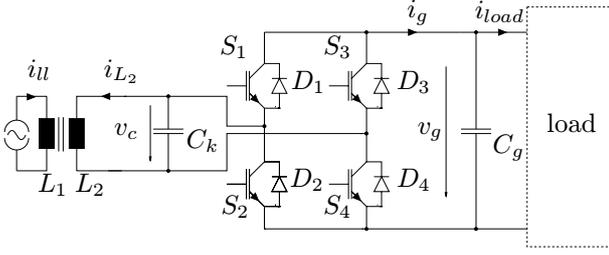

Figure 4: Converter with voltage clamping

The converter consists of the IGBTs S_1 to S_4 and diodes D_1 to D_4. The operation of the converter is illustrated by figure 5.
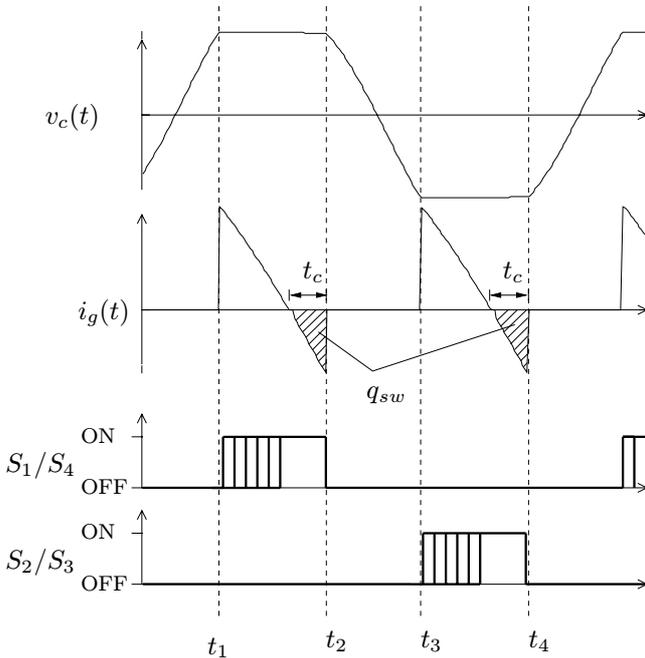

Figure 5: Operation of the converter

As long as the absolute value of the voltage v_c is lower than v_g the parallel resonant circuit consisting of C_k and L_2 is fed by the current i_{ll2}. If v_c reaches v_g (see t_1 in figure 5) the current through the capacitor C_k commutates to the diodes D_1 and D_4 connected in anti-parallel to the IGBTs S_1 and S_4. The voltage v_c is now clamped to v_g and energy is transferred to the load. During the conduction interval of the diodes D_1 and D_4 it is possible to turn on the IGBTs S_1 and S_4 under zero voltage condition. When the current i_g crosses zero the IGBTs S_1 and S_4 start conducting and energy is transferred back from the dc link to the primary pathway. As an effect of the parallel connected capacitor C_k the IGBTs can be switched off softly at t_2. The integral of the IGBT current, q_{sw}, can be increased by increasing the conduction interval t_c of the IGBTs to such an amount, that energy flow can be reversed. 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 and C_k is shorted and neither reactive nor active power is transmitted.

To ensure that the diodes start conducting the following equation has to be fulfilled:

$$\hat{i}_{ll2} \cdot \left| \frac{1}{\omega \cdot C_k - \frac{1}{\omega \cdot L_2}} \right| > v_g \tag{5}$$

As a result of using a parallel resonant circuit for both converters, the same differential equations, which describe the operation of the dc current link converter, describe the dc voltage link converter. The mathematical description of the converter results of the equations (1),(3),(4) and the smooth transition of the current i_{L_2} and the voltage v_c at t_1 and t_2.

A detailed analysis of the mathematical description will be shown in the final paper.

OPTIMIZING THE PARALLEL RESONANT CIRCUIT

Optimizing the size of the u-core for a given primary pathway means to optimize the parallel resonant circuit for a given set of parameters:

- the primary current i_{ll}
- the maximum load voltage $v_{g,max}$
- and the maximum transfer power P_{max}.

As free variables remain:

- the mutual inductance of the u-core,
- the number of secondary windings N_2
- and the compensation capacitance C_k.

The detection of the optimum number of secondary windings N_2 will be shown later. Assuming a fixed number of secondary windings N_2 the following optimization can be done.

The size of the u-core depends on the air-gap d and the cross-sections A_1 and A_2 shown in figure 6.
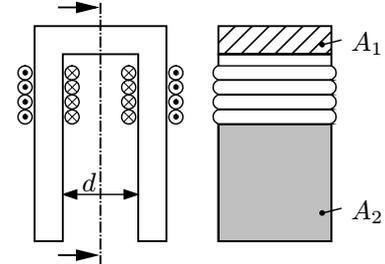

Figure 6: Dimensions of the u-core

The air-gap d depends on the necessary mechanical tolerance of the moving device. A_1 is given by the maximum flux Ψ_{max} at the maximum permissible fluxdensity B_{max} of the core-material.

$$A_1 = \frac{\Psi_{max}}{B_{max}} = k \cdot \frac{\hat{v}_c}{\omega \cdot B_{max} \cdot N_2} \tag{6}$$

In equation (6) k is a factor that describes the shape of $v_c(t)$. If $v_c(t)$ is sinusoidal k is 1. As the shape of $v_c(t)$ is influenced by C_k and L_2, this factor depends on these parameters, but this influence on A_1 is weak. So, at a given Ψ_{max} and B_{max}, the size of the core can only be altered by altering the cross-section A_2.

To get a common solution of the problem for every set of given parameters it is useful to describe the operation of the converters by using the per-unit quantities:

$$Param_1 = \frac{v_{g,max}}{\hat{i}_{ll2} \cdot L_2} \tag{7}$$

$$\omega_x = \frac{1}{\sqrt{L_2 \cdot C_k}} \tag{8}$$

This common solution is done by the following steps:

1. Calculating the function $P_{max}/(v_{g,max} \cdot \hat{i}_{ll2}) = f(\omega_x)$ with a fixed parameter $Param_1$ the optimum $\omega_{x,opt}$ with the maximum power $P_{max,opt}/(v_{g,max} \cdot \hat{i}_{ll2})$ is derived for this parameter $Param_1$.

2. Step 1 is done for several parameters $Param_1$. This results in two functions
$P_{max,opt}/(v_{g,max} \cdot \hat{i}_{ll2}) = f(Param_1)$ and
$\omega_{x,opt} = f(Param_1)$.

For the dc current link converter the function
$P_{max}/(v_{g,max} \cdot \hat{i}_{ll2}) = f(\omega_x, Param_1)$ can be derived by the following equations (9) and (10).

$$\sin\varphi = -\frac{T}{4} \cdot \frac{Param_1 \cdot (\omega_x^2 - w^2)}{\omega_x^2} \tag{9}$$

$$\frac{P_{max}}{v_{g,max} \cdot \hat{i}_{ll2}} = \frac{T}{4} \cdot Param_1 + \frac{\omega_x}{\sin(\omega_x \cdot \pi/\omega)} \tag{10}$$
$$\cdot \left(\cos(\varphi) \cdot \frac{\omega}{\omega^2 - \omega_x^2} \cdot (1 + \cos(\omega_x \cdot \pi/\omega)) \right)$$
$$+ \frac{\omega_x^2}{\omega_x^2 - \omega^2} \cdot \sin(\varphi)$$

Equation (11) gives the transferred power for the dc voltage link converter. The parameters t_1, t_2, t_3, φ and $i_{L_2}(0)$ are derived by additional equations. The complete set of equations which is necessary to calculate the functions $P_{max,opt}/(v_{g,max} \cdot \hat{i}_{ll2}) = f(Param_1)$ and $\omega_{x,opt} = f(Param_1)$ for the dc voltage link converter will be shown in the final paper.

$$\frac{P_{max}}{v_{g,max} \cdot \hat{i}_{ll2}} = \frac{\omega}{\pi} \cdot \left(-\frac{1}{\omega} \cdot (\cos(\varphi) + \cos(\omega \cdot (t_3 - t_2) + \varphi)) \right.$$
$$+ \frac{1}{2} \cdot Param_1 \cdot (t_2 - t_1)^2$$
$$\left. + \frac{i_{L_2}(0) + i_{ll2}(0)}{\hat{i}_{ll2}} \cdot (t_2 - t_1) \right) \tag{11}$$

The solutions at a frequency of the primary current of 25 kHz for both converters described above are shown in figure 7 and 8.
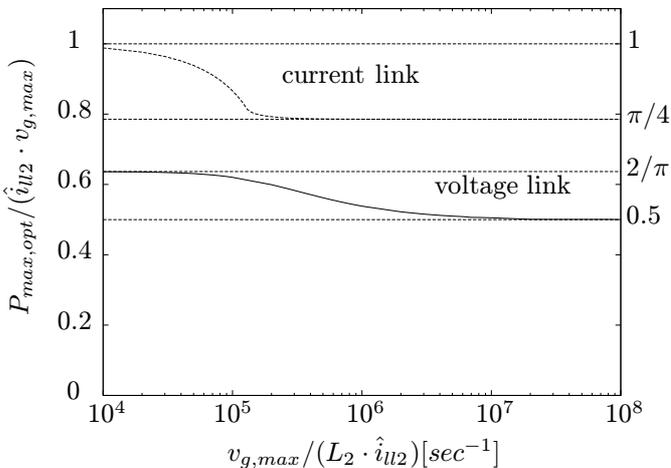

Figure 7: $P_{max,opt}/(\hat{i}_{ll2} \cdot v_{g,max}) = f(Param_1)$

Figure 7 shows that with a larger parameter $Param_1$, which results in a smaller secondary inductance L_2, the maximum transfered power for both converters is decreasing. So for every set of parameters consisting of P_{max}, i_{ll2} and $v_{g,max}$ the smallest secondary inductance L_2 can be determined by figure 7.
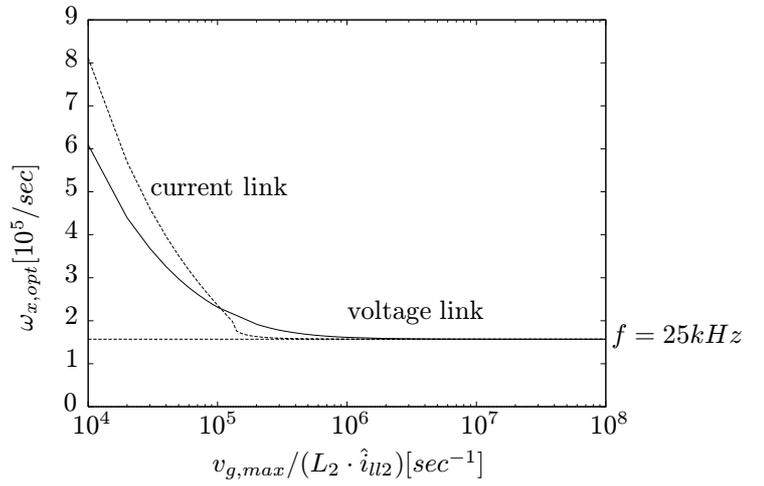

Figure 8: $\omega_{x,opt} = f(Param_1)$

If the parameter $Param_1$ is determined by figure 7 the optimum capacitance can be chosen by figure 8.

As shown above it is possible to optimize the size of the u-core for a fixed number of secondary windings N_2. To get the smallest u-core for the given parameters $\hat{i}_{ll}$, $v_{g,max}$ and P_{max} the number of secondary windings has to be chosen as high as possible. The limits for the convertertypes are given by the maxima of $P_{max,opt}/(\hat{i}_{ll2} \cdot v_{g,max})$ shown in figure 7.

Furthermore it can be seen, that the dc current link converter is able to transfer more power than the dc voltage link converter. On the other hand the dc voltage link converter has the ability to recover energy, a better open circuit behaviour and the possibility of no-load operation.

CONCLUSION

This paper has presented a new method to optimize the size of the tranformer-core of a magnetic power transfer system for linear movable devices. It was proved that this method is suitable for dc current link and dc voltage link converters. The mathematical description which is necessary for the proposed optimization method will be shown in the final paper. A comparison of the proposed converters concerning the size of the transformer u-core at a primary current with a frequency of 25 kHz was done. Furthermore a contactless power transfer system with reduced electromagnetic emission was proposed.

References

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[4] S. Nishino and J.T. Boys. A primary inductive pathway. patent no. WO 93/23909, November 1993.

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