THE LEAKAGE INDUCTANCE DEPENDENCE ON HF TRANSFORMER WINDING ARRANGEMENT

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Abstract: The series resonant converter often uses the leakage inductance of transformers as resonant inductance in series with resonance capacitor. So the resonant capacitor is used to compensate the leakage inductance on set switching frequency. The leakage inductance of transformer can be affected in wide range, just by different arrangement of transformer windings around the core. It means that in the most cases the additional inductor needn't to be used.

Keywords: resonant converter, leakage inductance, series resonant converter, transformer

1. INTRODUCTION

There are two main types of switching converters. The most expanded converters are hard-switching ones. These converters are easy to control, usually by pulse-width modulation, so we can control output voltage easily by changing width of switching pulses. This control allows us to drive output voltage from 0% to 100% continuously. The main disadvantage of hard-switching converters, are high switching losses. To reduce these losses, we can use snubber circuits to limit the loss energy during the switch-on or switch-off process.

The second main type of converters, are soft-switching ones. Their main advantage is limitation of switching losses from the principle of its working. They work in ZCS (zero current switching) regime, see [2], [3], ZVS (zero voltage switching) regime, see [4], [5], or combination of both. But there is a big disadvantage. The soft-switching converters are hard to control. If they work in nominal point, with nominal output voltage and nominal load, there are no switching losses. But if we need to control the output voltage in the wide range, then we need to switch on the transistor in the time instant, when the voltage on transistor isn´t equal to zero (non ZVS) or switch off when the current isn´t equal to zero (non ZCS).

2. SERIES RESONANT CONVERTER

In this converter, the resonant elements are connected in series. This connection can be used with advantage for compensating leakage inductance of transformer. The basic connection is shown in Figure 1.

In this case, the resonant capacitor C_r is in series resonance with leakage inductance L_r of transformer and the resonant frequency is given by:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

where L_r is given by:

$$L_r = L_1(1-k^2) \tag{2}$$

where L_1 is the primary inductance of transformer and k is the coupling coefficient between transformer windings.

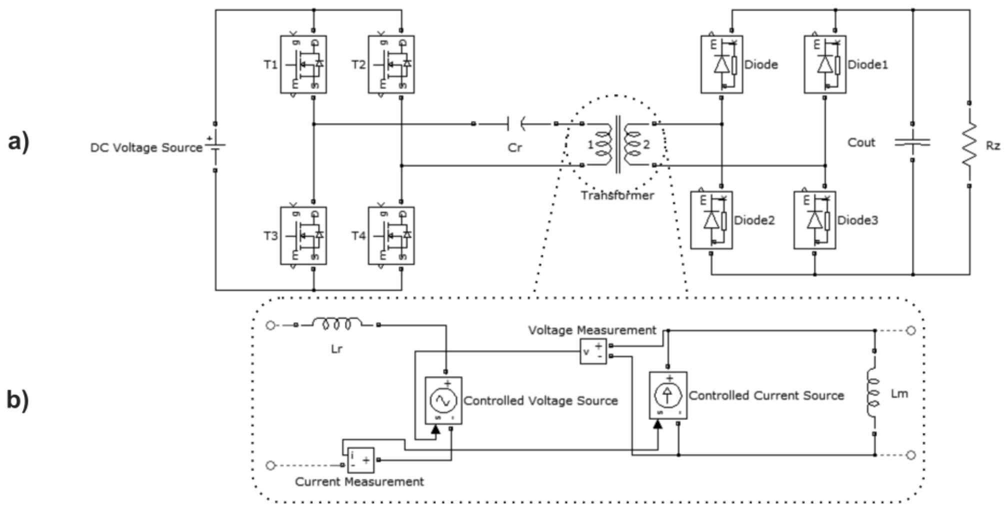

Figure 1: a) Basic connection of Full bridge series resonant converter. b) Equivalent model of transformer [1].

2.1. The role of leakage inductance

The series resonant converter often uses the leakage inductance of transformer as resonant inductance in series with resonance capacitor. So the resonant capacitor is used to compensate the leakage inductance on set switching frequency. If we construct the transformer for switching supply, the leakage inductance can be measured, as will be shown below. The switching frequency is given due to speed of switching transistors, secondary diodes, transmitted power and material of transformer core. Then, the required capacitance of resonant capacitor is given by (3).

$$C_r = \frac{1}{4\pi^2 f_r^2 L_r} \tag{3}$$

where L_r is measured and f_r is set.

2.2. Measuring the leakage inductance

To measure the leakage inductance of transformer, we need accurate LC-meter. For identification of all transformer parameters, we need to measure four values:

L_1 – primary inductance, secondary winding is open

$L_{1,k}$ – primary inductance, secondary winding is short-connected

L_2 – secondary inductance, primary winding is open

$L_{2,k}$ – secondary inductance, primary winding is short-connected

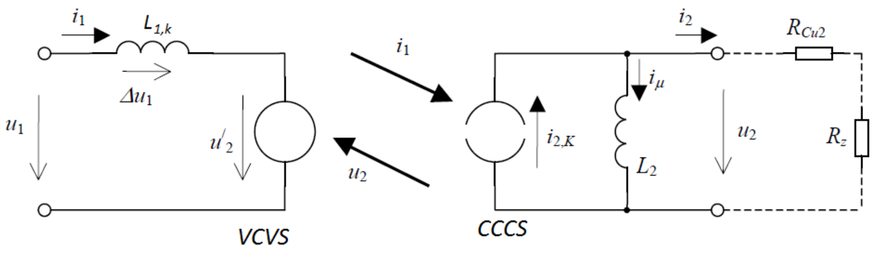

Figure 2 - Equivalent connection of transformer [1], VCVS - voltage controlled voltage source, CCCS - current controlled current source

As shown in Figure 2, the leakage inductance is measured directly, when the secondary winding is short-connected. Then, we are able to calculate the coupling coefficient k between transformer windings:

$$k = \sqrt{1 - \frac{L_{1,k}}{L_1}} \tag{4a}$$

$$k = \sqrt{1 - \frac{L_{2,k}}{L_2}} \tag{4b}$$

From the principle of reciprocity it follows, that the ratios $\frac{L_{1,k}}{L_1}$ and $\frac{L_{2,k}}{L_2}$ must be equal. The prospective slight inequality is caused by the imperfetcion of the measure process.

3. THE LEAKAGE INDUCTANCE DEPENDENCE ON TRANSFORMER WINDING ARRAGEMENT

The leakage inductance can be affected by geometrical arrangement of transformer windings. Two types of transformers were manufactured and measured with different winding arrangements, as shown below.

3.1. TRANSFORMER WITH 1:1 RATIO

The first transformer was wind with the parallel wires together around the whole transformer core, see Figure 3. It is possible to expect, that this type would have the best coupling coefficient (closest to 1).

Figure 3 - The 1:1 transformer, windings together

This transformer has 10 primary and 10 secondary turns. The measured parameters are:

$$L_{1,k} = 443\text{nH}$$
$$L_1 = 336\mu\text{H}$$
$$L_{2,k} = 448\text{nH}$$
$$L_2 = 335{,}6\mu\text{H}$$

Then the coupling coefficient k was calculated according to equations (4a,b):

$$k = \sqrt{1 - \frac{443\text{nH}}{336\mu\text{H}}} = \sqrt{1 - \frac{448\text{nH}}{335{,}6\mu\text{H}}} = 0{,}9993$$

The second 1:1 ratio transformer was wind differentially. 10 turns of each winding are on the other side of the core. As shown below:

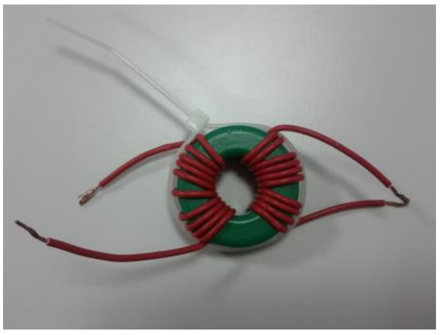

Figure 4 - 1:1 transformer, windings on other sides

This transformer has 10 primary and 10 secondary turns. The measured parameters are:

$$L_{1,k} = 8{,}13\mu\text{H} \quad L_{2,k} = 8{,}11\mu\text{H}$$
$$L_1 = 327{,}3\mu\text{H} \quad L_2 = 327\mu\text{H}$$

Then the coupling coefficient *k* was calculated according to equations (4a,b):

$$k = \sqrt{1 - \frac{8{,}13\mu\text{H}}{327{,}3\mu\text{H}}} = \sqrt{1 - \frac{8{,}11\mu\text{H}}{327\mu\text{H}}} = 0{,}987$$

As we can see, the transformers have same ratio. And just by different winding arrangement, the leakage inductance has grown from 443 nH to 8,13 μH, which is almost 20 times more.

3.2. TRANSFORMER WITH 10:1 RATIO

The first transformer was wind with windings on other sides of the core. As shown below:

Figure 5 - The 10:1 transformer, windings on other sides

This transformer has 10 primary turns and 1 secondary turn. The measured parameters are:

$$L_{1,k} = 19{,}1\mu\text{H} \quad L_{2,k} = 135\text{nH}$$
$$L_1 = 323\mu\text{H} \quad L_2 = 3{,}28\mu\text{H}$$

Then the coupling coefficient *k* was calculated according to equations (4a,b):

$$k = \sqrt{1 - \frac{19{,}1\mu\text{H}}{323\mu\text{H}}} = \sqrt{1 - \frac{135\text{nH}}{3{,}28\mu\text{H}}} = 0{,}97$$

The second 10:1 ratio transformer was wind differentially. 10 turns of primary winding are wind equally around the whole core and the secondary winding consists of 6 turns wind equally around the whole core and connected in parallel, as shown below:

Figure 6 - 10:1 transformer, 6 turns of secondary winding, connected in parallel

This transformer has 10 primary turns and 6 secondary turns connected in parallel. The measured parameters are:

$$L_{1,k} = 3{,}44\mu\text{H} \qquad L_{2,k} = 18\text{nH}$$

$$L_1 = 316\mu\text{H} \qquad L_2 = 3{,}03\mu\text{H}$$

Then the coupling coefficient k was calculated according to equations (4a,b):

$$k = \sqrt{1 - \frac{3{,}44\mu\text{H}}{316\mu\text{H}}} = \sqrt{1 - \frac{18\text{nH}}{3{,}03\mu\text{H}}} = 0{,}996$$

As we can see, the transformers have same ratio. And just by different winding arrangement, the leakage inductance has grown from 3,44 μH to 19,1 μH, which is almost 6 times more.

4. CONCLUSION

This article shows, that the leakage inductance of transformer can be affected in wide range, just by different arrangement of transformer windings around the core. It means that in the most cases the additional inductor needn't to be used. In the cases only, when the inductance must be extremely higher as the value of the leakage inductance is, the additional inductor must be connected in series with the transformer winding.

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