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Converter Transformers manufactured for the Slovenian Railways

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Abstract. The paper contains an overview of the most significant technical characteristics of converter transformers manufactured to modernize the Slovenian Railways. The main features and characteristics of this type of the traction drives with various intersected winding configurations are described. The referenced projects include the first application of axial winding crossing, i.e. a technological innovation resolving the strong magnetic coupling requirement of low-voltage windings. The solution is referred to as an intersected winding. With one, two and three winding crossings the coupling factors of 0.920 and 0.967 are achieved. The results meet the specifications of the SIST EN standard.

Keywords: converter transformer, designer, coupling factor, intersecting winding

1 INTRODUCTION

When designing and planning power projects, design engineers look for the optimal solution, which usually begins with an assessment of the overall cost of materials of the transformer.

The procedure of designing special transformers is similar, yet it is run in parallel with a practical optimal solution that is determined mostly by technological and feasibility restrictions. Consequently, such projects present the problem of feasibility and are seldom considered for optimization.

The first converter transformer was manufactured in 1993 for the ENP Sava power substation. As seen from table 1 the transformer supplies a bridge-type converter in parallel connection by using an interbridge reactor, connection no. 9 [4] [5]. The transformers manufactured in 1997 and 2011 were designed for a serial bridge converter, connection no. 12. The transformers were installed in three different power substations.

Technical requirements for each of the three transformers were the same.

2 MAIN REQUIREMENTS AND RESTRICTIONS

The converter transformers for DC traction drive are special transformers meeting particular requirements. For the purpose of this paper requirements specifying only coupling factor and short-circuit impedance with set tolerance will be dealt with.

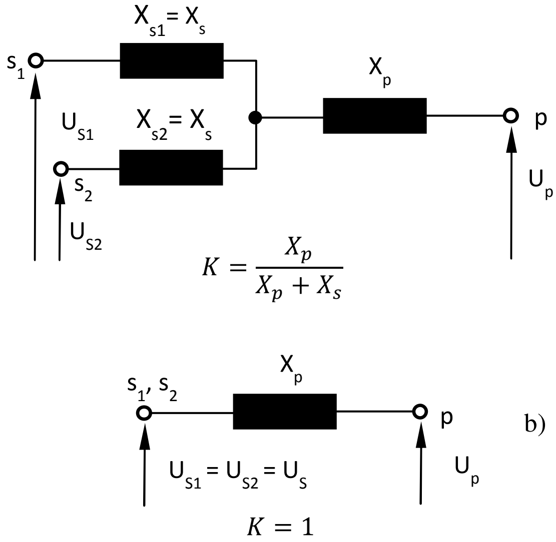

Figure 1. Converter transformer equivalent circuit

2.1 *Coupling factor*

According to standard [4], the leakage reactance ratio or the coupling factor must be $K > 0.9$. It is derived from three winding transformer equivalent circuit (Fig. 1.) :

$$K = \frac{X_p}{X_p + X_s}\ , \tag{1}$$

and:

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Table 1. Survey of Converter Transformers

Substation		***ENP SAVA***	***ENP ČRNOTIČE***	***ENP DEKANI***
Transformer designation		**UNT 3650**	**UNT 5460**	**URT 7272**
Installation		Outdoor		
Insulation liquid		Mineral oil		
Number of phases		3		
Rated frequency	Hz	50		
Type of cooling		ONAN		
Maximum ambient temperature	°C	40		
Rated power	kVA	3650/2 x 1890	5460/2 x 2830	7272/2 x 3770/50
Overloading		class VI		
Rated voltage at no-load	kV	35(20.2)/2 x 2.67	20/2 x 1.335	114/2 x 1.332/0.4
Highest voltage for equipment	kV	36/7.2	24/7.2	123/7.2
Insulation level LI (1.2/50) / AC (1'): HV winding	kV	170/70	125/50	550/230
LV winding	kV	40/20		
Connection symbol		Yy0d11(Dy1d0)	Dy11d0	Yy0d11+syn0*
Voltage regulation		Off load ± 4 x 2.5 %	Off load + 1/ -3 x 2.5 %	On load ± 8 x 1.25 %
Maximum temperature rise: oil / winding	K	60/65		
Short-circuit impedance HV/LV	%	8.3	8.9	10.8
Mass: Oil / Total	t	2.3 / 12	2.9 / 14.5	10.5 / 31
* Auxiliary winding 50 kVA- 400 V				

$$\begin{aligned} X_p &= \frac{X_{ps1} + X_{ps2} - X_{s1s2}}{2} \\ X_{s1} &= \frac{X_{ps1} - X_{ps2} + X_{s1s2}}{2} \cong X_s \\ X_{s2} &= \frac{X_{ps2} - X_{ps1} + X_{s1s2}}{2} \cong X_s \end{aligned} \qquad (2)$$

Though the leakage reactance is a calculated equivalent value with no physical meaning, it is nonetheless a good estimate for analyzing different operating states of the electric grid. This also applies to the coupling factor calculation determined by using the leakage reactance ratio. Analyzing the converter drives shows that ratio K significantly impacts the transformer under different operating conditions, the external characteristic being most important. A common operating condition occurs when one of the low voltage windings is off load and the other is under full load. A high coupling factor can reduce the difference in voltages on the secondary side. Because of such special operating condition, the equivalent circuit for converter transformers is more distinct.

Because of the intersecting winding symmetry, the difference between leakage reactance X_{ps1} and X_{ps2} and their arithmetic mean value is negligible (less than 0.2 %). The equivalent reactance of the secondary winding is derived from:

$$X_{s1} = X_{s2} = X_s = \frac{X_{s1s2}}{2} \qquad (3)$$

$(X_{\mathrm{ps1}} = X_{\mathrm{ps2}})$.

The magnetic coupling factor is defined as the ratio of mutual inductance M and self-inductances Ls_1 and Ls_2 [2].

The magnetic coupling factor can be calculated from the equation:

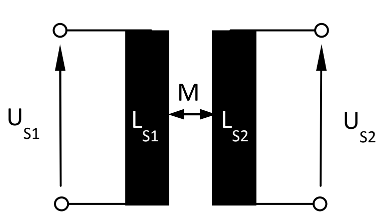
$$k = \frac{M^2}{L_{s1} \cdot L_{s2}}\,, \qquad (4)$$

which is applicable only for transformers with two windings. The magnetic coupling factor of power transformers is very close to 1, in the case shown in Fig. 3d, it is k = 0.999997 and in Fig. 3a k = 0.999956. To determine the difference between two different solutions the factor k must be determined precisely. Regardless of the position of the windings, the magnetic coupling factor is always $k < 1$.

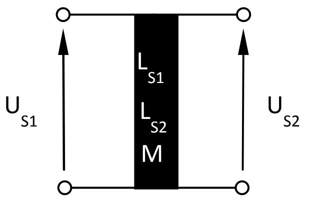
The converter-transformer coupling factor is affected by the magnetic coupling of the low-voltage windings (k). The condition where $k = K = 1$ is possible only in theory, while in practice it is $k > K$.

A better interpretation of the coupling efficiency of windings s_1 and s_2 is their leakage reactance declared as a percentage which is also attained by a relatively simple calculation. In practice, the condition $X_{\mathrm{s1s2}} > 0$ is always true.

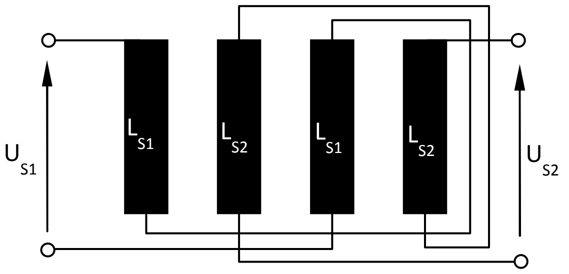
It is only in theory that the magnetic leakage of two windings equals zero, if such be the case, the two windings would occupy the same space (Fig. 2b.). In practice such condition is hard to attain. Each winding should be divided into small sections surrounded by sections of the other windings. Dividing each winding into six sections with three crossings produces a leakage reactance of low-voltage windings X_{s1s2} = 0.7 % (Fig. 3d.).



a) $k \cong 1$, $X_{s1s2} > 0$



b) $k = 1$ ($L_{S1} = L_{S2} = M$), $X_{s1s2} = 0$



c) $k \cong 1$, $X_{s1s2} > 0$

Figure 2. Coupling factor for low-voltage windings

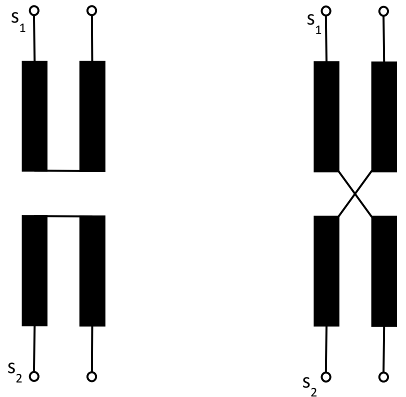
At such low values of leakage reactance, leads and winding connection too, can be strongly impacting. This is why the coils were turned on the winding machine during the winding process. The procedure was performed after each crossing so that connections between sections were the shortest possible, thus reducing the impact of leads on the leakage reactance. The crossing between sections was uninterrupted.

For high currents above 1 kA the cross section of the low-voltage connections between sections is large. Short connections contribute to a lower short-circuit loss and additional losses in the transformer windings.

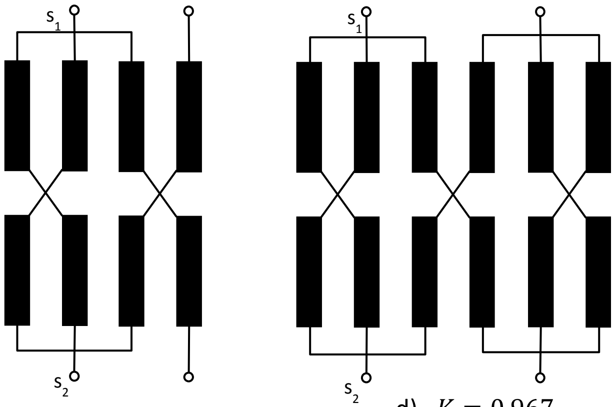
The equivalent reactance of the primary and secondary windings are $X_p = 10.35$ %, $X_s = 0.35$ %.

Because of $X_p >> X_s$, the equivalent circuit of the three-winding transformer can be replaced with a two-winding equivalent circuit with only one reactance X_p and one secondary voltage $U_{s1} = U_{s2} = U_s$ (Fig. 1b.).

Strong coupling improves the stability of the converter drive because different loadings on the low- voltage sides do not cause different voltages on its side. For dynamic operation with frequent overloading, this is very advantageous for the converter transformer. Coupling of the winding with six sections and three crossings shown in Fig. 3d produces $K = 0.967$, which is not much less than the theoretical $K = 1$.



a) $K = 0.1$ b) $K = 0.8$



c) $K = 0.92$ d) $K = 0.967$

Figure 3. Intersecting the winding with one (b), two (c) and three crossings (d)

2.2 Tolerances

The limit maximum deviations of the arithmetic mean of the short-circuit impedances between winding pairs s_1-p and s_2-p should not exceed the tolerance of ± 1.5 %. For power transformers the tolerances are in the range from ±7.5 % to ±10 %. This requirement implies that both parallel voltage sides of the converter units are strongly symmetrical, thus assuring the stable operation of the converter and transformer. Calculations and final measurements reveal deviations of the short-circuit impedances in the range of ± 0.2 %, which is near the equipment measuring certainty. The solution to intersect the low-voltage winding assures an almost perfect geometrical symmetry of both the low-voltage to the supply side.

2.3 Short-circuit impedance

The short-circuit impedance of low-voltage windings s_1 and s_2 should not exceed the value of 2 %. This requirement is very restrictive if we consider that the ohmic component can be 1 %, which means that the inductive component must be below 1.7 %. This condition is even worse in case of high losses transformer. To avoid this problem we developed a new way of winding enabling the leakage level to be low and at the same time the low-voltage windings against the high-voltage winding were geometrically symmetric. The solution shown in Fig. 2c does not enable these requirements to be achieved. The case in Fig. 3a is technologically very simple, but with the weakest coupling at 0.1. Considering that one low-voltage winding is delta-connected and the other one star-connected, their interleaving could be difficult or even impossible to achieve. The difference in the number of turns in the low-voltage windings and dividing in four or six sections complicate the interleaving even further, especially for large power transformers, with a low number of turns. Another problem is the insulation inside the windings, which have to be insulated for the full test voltage.

The short-circuit impedance for the connection shown in Fig. 3d was $u_{ks1s2} = 1.2$ %.

Table 2. Summary of the measured and requested values

Requirement [4]	*Measurement*
$K > 0.9$	$K = 0.967$
$\Delta u_{kps} = \pm 1.5$ %	$\Delta u_{kps} = \pm 0.2$ %
$u_{ks1s2} = 2$ %	$u_{ks1s2} = 1.2$ %

Table 2 shows the most important parameters. The results are comparable with the SIST EN [4] specifications. The data is obtained from the final measurements made at the ENP Dekani project.

3 CONCLUSION

The coupling factor of the converter transformer is the ratio of the equivalent leakage reactance as defined in equation (1). It depends on the efficiency of the magnetic coupling of the secondary windings in equation (4) and is determined by the design and arrangement of the windings. This ratio is a significant characteristic of the converter transformer as it affects stability of the DC traction. It defines the external characteristics of the converter in suppressing short-circuit currents often occurring in converters driving with frequent overloads [3]. The improved coupling factor with the value of 0.967 exceeds the required 0.9 set in the SIST EN standard. This provides a more stable external characteristic of the converter and lower value the short-circuit currents in the transformer windings and the converter itself.

When modernizing the Slovenian Railways, we manufactured converter transformers that comply with the requirements for supplying converters in two different connections of converters 9 and 12. To achieve this, we developed a new method of winding the low-voltage coils with multiple intersections and minimal connections between them. Because of the characteristic intersection between sections of the windings we named it the intersected winding. These windings can also be used in other types of power transformers.

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Juso Ikanović graduated from the Faculty of Electrical Engineering of the University of Ljubljana in 1976. He holds a Master's degree from the Faculty of Electrical Engineering at the University of Zagreb. Since his first employment in 1977 (Energoinvest TTL) he has been involved in designing and constructing special power transformers. He is currently continuing his work at the Kolektor Etra d.o.o. plant and has published several papers in this field in the Electrotechnical Review and the national committees of Sloko CIGRE and Juko CIGRE (former Yugoslavian committee).