MODELING OF MULTI-WINDING PHASE SHIFTING TRANSFORMERS APPLICATIONS TO DC AND MULTI-LEVEL VSI SUPPLIES

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ABSTRACT

This paper deals with the modeling of multi-winding transformers. Based on the real example of a railway DC - supply, a modeling methodology is presented as the original part of the paper. Afterwards two application examples of multi-winding phase shifting transformers (18 and 24 pulse) are described, these applications have been simulated using the *SIMSEN* simulation software package [1,2]. Harmonics analysis of simulation results (elimination of low order harmonics 5, 7, 11, 13) has validated the proposed methodology.

Keywords: Multi-winding transformer, phase shifting, harmonics reduction, DC supply, simulation, harmonics analysis.

1 INTRODUCTION

The DC power supplies are made of rectifiers [3]. Those are providing harmonics leading to a great inconvenience for the power networks. Even if additional L-C filters are able to absorb the most important part of the harmonics content, they may introduce resonance problems. A more suitable solution is to increase the pulse number of the rectifiers. This requires phase shifting transformers having multi-windings [4]. The most complex part to modelize such special transformers is the determination of all the needed parameters: inductance and resistance values for each winding, coupling coefficients between all the considered windings. These parameters must be determinated using the measurements obtained from the typical tests under no-load and short circuit conditions.

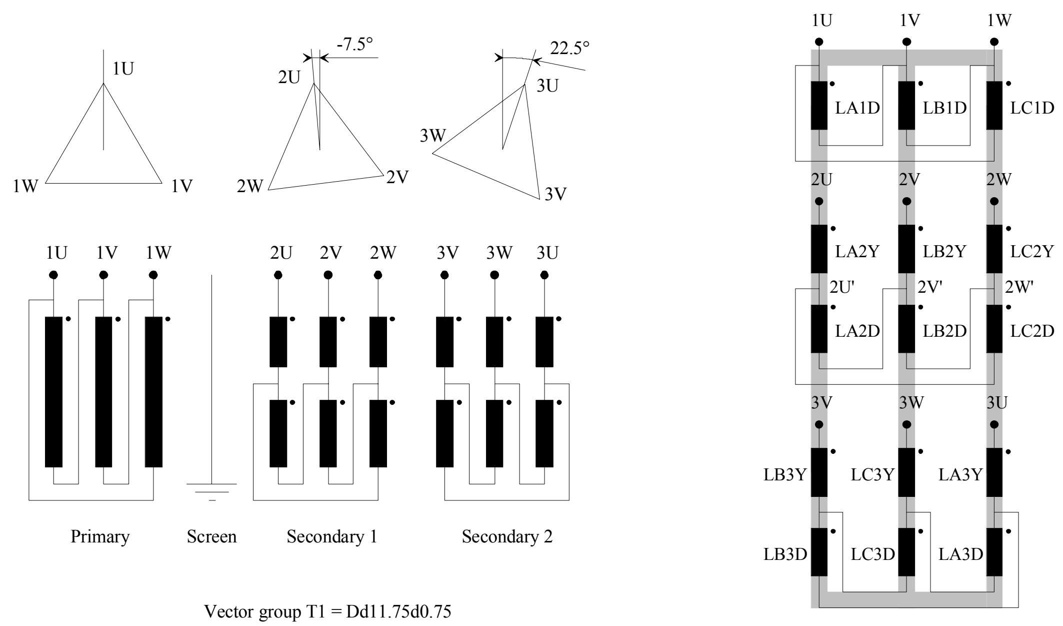

Figure 1 - Multi-winding phase shifting transformer example

2 METHODOLOGY

2.1 Systematic names definition

The developed methodology is explained using the multi-winding phase shifting transformer example given in the left part of Fig. 1. The initial stage is to define the different names and indexes for inductances and to use for the development, as shown in the right part of Fig. 1:

L	Inductance
X	phase x (a, b, c)
I	winding I (1, 2, 3…)
Y/D	star/delta connection

Example: LB2D inductance, phase b, winding 2, delta-connected.

The different coupling coefficients also have to be defined carefully:

k	Coefficient
i	winding i (1, 2, 3…)
y/d	start/delta connection
j	winding j (1, 2, 3…)
y/d	star/delta connection

Example: k1d2y coupling coefficient between delta-connected winding 1 and star-connected winding 2.

2.2 Necessary input data

The necessary input data correspond to the data plate of the transformer as well as some additional measurements coming from the typical tests under no-load and short circuit conditions. These input data are:

SN1	=	3146 kVA	apparent power.
UN1	=	22 kV	primary side line voltage.
FN	=	60 Hz	frequency.
UN20	=	569 V	secondary 1 line voltage (no-load)
UN30	=	569 V	secondary 2 line voltage (no-load)
i0	=	0.00569 p.u.	no-load primary side current.
xcc12	=	0.0878 p.u.	short circuit reactance 1-2, 3 open.
xcc13	=	0.0878 p.u.	short circuit reactance 1-3, 2 open.
xcc23	=	0.0112 p.u.	short circuit reactance 2-3, 1 open
R1	=	0.611 Ohm	primary terminal resistance.
R2	=	0.00088 Ohm	secondary 1 terminal resist.
R3	=	0.00104 Ohm	secondary 2 terminal resist.

2.3 Stray reactances in per unit

In a first stage, the stray reactances (xs1, xs2 and xs3) of each terminal are calculated in [p.u.]:

$$xs1 = \frac{xcc12 + xcc13 - xcc23}{2} = 0.0822 \text{ p.u.} \tag{1}$$

$$xs2 = \frac{xcc12 + xcc23 - xcc13}{2} = 0.0056 \text{ p.u.} \tag{2}$$

$$xs3 = \frac{xcc13 + xcc23 - xcc12}{2} = 0.0056 \text{ p.u.} \tag{3}$$

2.4 Primary winding inductances

For the primary winding, the rated impedance ZN1Y is first calculated according to equation (4):

$$ZN1Y = \frac{UN1^2}{SN1} = 153.8 \text{ Ohm} \tag{4}$$

Using equations (1) and (4), the equivalent star-connected stray reactance XS1 is:

$$XS1 = xs1 \cdot ZN1Y = 12.64 \text{ Ohm} \tag{5}$$

The star-connected equivalent no-load impedance Z1Y is calculated taking into account the no-load current i0:

$$Z1Y = \frac{1}{i0} \cdot ZN1Y = 27.04 \text{ kOhm} \tag{6}$$

Using the angular frequency, the equivalent star-connected inductance L1Y is calculated:

$$L1Y = \frac{Z1Y}{2 \cdot \pi \cdot FN} = 71.72 \text{ H} \tag{7}$$

To obtain the delta-connected inductance L1D, the previous value has to be multiplied by 3:

$$L1D = 3 \cdot L1Y = 215.2 \text{ H} \tag{8}$$

Doing the same operation for the delta-connected stray inductance LS1D, we obtain:

$$LS1D = \frac{3 \cdot XS1}{2 \cdot \pi \cdot FN} = 0.1006 \text{ H} \tag{9}$$

Finally, the main delta-connected inductance LH1D is:

$$LH1D = L1D - LS1D = 215.1 \text{ H} \tag{10}$$

2.5 Secondary 1 winding inductances

The mathematical development is based on the elements represented in Fig. 2.
For the secondary 1 winding (index 2), the desired phase shifting angle is equal to –7.5°. This means that this secondary winding has to be a combination of Dy11 (-30°) and Dd0 (0°). The first step is to define the ratios n2y/n1d

and n2d/n1d between the turns numbers of the windings 2Y, 2D and 1D according to the equations (11) and (12):.

$$\frac{n2y}{n1d} = a \tag{11}$$

$$\frac{n2d}{n1d} = b \tag{12}$$

The phase angle between the line voltages $U_{1U\text{-}1V}$ and $U_{2U\text{-}2V}$ must be 7.5 °. The line voltage $U_{2U\text{-}2V}$ is the sum of the three partial voltages: $U_{2U\text{-}2U'}$, $U_{2U'\text{-}2V'}$, $U_{2V'\text{-}2V}$, as represented in Fig. 2.

$$\overline{U}_{2U-2V} = a.\overline{U}_{1U-1V} + b.\overline{U}_{1U-1V} - a.\overline{U}_{1V-1W} \tag{13}$$

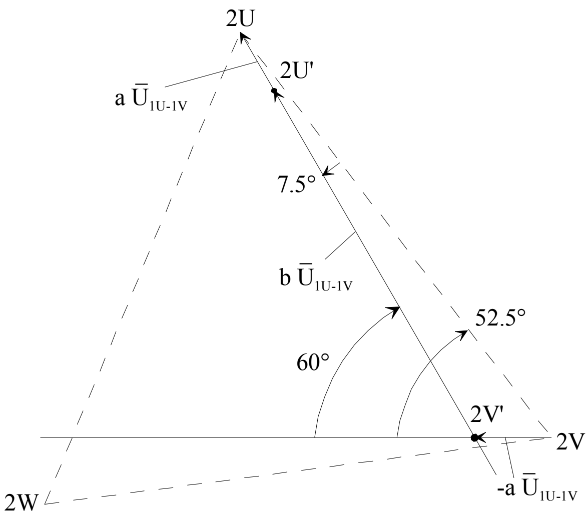

Figure 2 – Vector diagram for the secondary 1 winding

Under the assumption that primary and secondary line voltages are equal (a and b become a’ and b’ in equations 11 and 12) and by taking into account the angles at points 2V’ and 2V equal to 60° and 60 – 7,5 = 52,5°, the projections of equation (13) on both horizontal and vertical axis lead to:

$$\begin{aligned} &\cos 60^{o}.\ a' + \cos 60^{o}.\ b' + a' = \cos 52.5^{o} \\ &\sin 60^{o}.\ a' + \sin 60^{o}.\ b' = \sin 52{,}5^{o} \end{aligned} \tag{14}$$

and finally:

$$a = \frac{n2y}{n1d} = a'.\frac{UN20}{UN1} = 0{,}00389819 \tag{15}$$

$$b = \frac{n2d}{n1d} = b'.\frac{UN20}{UN1} = 0{,}019795 \tag{16}$$

The delta-connected inductance L2D is:

$$L2D = \left(\frac{n2d}{n1d}\right)^2 \cdot L1D = 84.31\,\text{mH} \tag{17}$$

Doing the same for the star-connected inductance L2Y, we obtain:

$$L2Y = \left(\frac{n2y}{n2d}\right)^2 \cdot L2D = 3.269\,\text{mH} \tag{18}$$

The equivalent star-connected stray reactance is calculated using equations (2):

$$XS2 = xs2 \cdot ZN1Y \cdot \left(\frac{UN20}{UN1}\right)^2 = 0.5763\ \text{mOhm} \tag{19}$$

The corresponding inductance is:

$$LS2 = \frac{XS2}{2 \cdot \pi \cdot FN} = 1.528\ \ \text{H} \tag{20}$$

Now, the global stray inductance LS2 has to be distributed on both star/delta-connected part of the secondary 1 winding. Therefore, a total equivalent star-connected inductance L2YTOT has to be defined:

$$L2YTOT = L2Y + \frac{1}{3} \cdot L2D = 31.37\,\text{mH} \tag{21}$$

Then, the star-connected stray inductance is:

$$LS2Y = \frac{L2Y}{L2YTOT} \cdot LS2 = 0.159\ \ \text{H} \tag{22}$$

The remaining delta-connected stray inductance LS2D is:

$$LS2D = 3 \cdot (LS2 - LS2Y) = 4.108\ \ \text{H} \tag{23}$$

Finally, the two main inductances of the secondary 1 winding are deduced:

$$LH2D = L2D - LS2D = 84.31\,\text{mH} \tag{24}$$

$$LH2Y = L2Y - LS2Y = 3.269\,\text{mH} \tag{25}$$

For all the secondary 1 winding, the total, main and stray inductances have been defined for both star/delta-connected windings. The same operations can be applied to the secondary 2 winding.

2.6 Coupling coefficients

The last step is to define the coupling coefficients between all the windings. The coefficients are calculated with the assumption that the 3 magnetic columns of the transformer are symmetrical. This leads to a magnetic coupling coefficient km equal to –0.5 between the columns. Two examples of coupling coefficients are calculated in equations (26,27):

$$k1d2d = \sqrt{\frac{LH1D \cdot LH2D}{L1D \cdot L2D}} = 0.9997 \tag{26}$$

$$k1d2y = \sqrt{\frac{LH1D \cdot LH2Y}{L1D \cdot L2Y}} = 0.9997 \tag{27}$$

2.7 Winding resistances

Finally, the resistance of each winding is calculated according to the measured terminal resistance and the related connections. For the primary winding, this is easy, because the terminal resistance is equal to the winding resistance (delta-connection).

$$R1D = R1 = 0.611\,\text{Ohm} \tag{28}$$

With the assumption that the resistance is proportional to the square root of the inductance, we can write:

$$R2Y = \frac{R2}{2 + \sqrt{\frac{L2D}{L2Y}}} = 0.1243\ \text{mOhm} \tag{29}$$

$$R2D = \sqrt{\frac{L2D}{L2Y}} \cdot R2Y = 0.6313\ \text{mOhm} \tag{30}$$

3 MODELING AND IMPLEMENTATION IN SIMSEN

The *SIMSEN* simulation software has been developed to simulate electrical power and adjustable speed drive systems having an arbitrary topology [1,2]. A given system topology (i.e. fig. 3 and 6) is built by choosing and linking the different necessary elements or modules from a module's list. The actual module's list of SIMSEN offers about one hundred modules, one of them is the so-called "linked inductor", this module is suitable for modeling multi-winding transformers.
Table 1. shows the input data for one linked inductor. In the section - LINKED INDUCTORS - all the coupled linked inductors as well as their related coupling coefficients are mentioned.

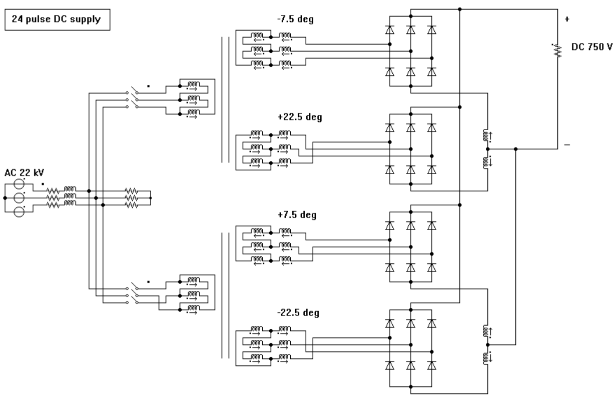

Figure 3 - 24-pulse DC supply for railway substation.

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- GENERAL DATA :

Name     = T1LA1D
Comment =
Writing = SI

- LINKED INDUCTORS :

;T1LA1D
T1LB1D -k1d1d*km
T1LC1D -k1d1d*km
;---------------
T1LA2Y  k1d2y
T1LB2Y -k1d2y*km
T1LC2Y -k1d2y*km
;---------------
T1LA2D  k1d2d
T1LB2D -k1d2d*km
T1LC2D -k1d2d*km
;---------------
T1LA3Y -k1d3y*km
T1LB3Y  k1d3y
T1LC3Y -k1d3y*km
;---------------
T1LA3D -k1d3d*km
T1LB3D  k1d3d
T1LC3D -k1d3d*km

- RATED VALUES:

Sn  [VA] =  0.00000000000E+0000
Un   [V] =  0.00000000000E+0000
Fn  [Hz] =  0.00000000000E+0000

- PARAMETERS :

R  [Ohm] =  6.11000000000E-0001
L    [H] =  2.15161475046E+0002

- INITIAL CONDITIONS:

I    [A] =  1.37001402709E+0001

- CALCULATED VALUES:

Leff [H] =  2.15161475046E+0002
```

Table 1. Input data for linked inductor T1LA1D

The *SIMSEN* simulation software automatically takes into account all the differential equations of a multi-winding transformer defined with linked inductors. The fact that a linked inductor can be coupled with an infinite number of other linked inductors is one of the *SIMSEN's features*, it makes possible combining any kind of magnetic coupled circuits.

For further information: http://simsen.epfl.ch

4 APPLICATION EXAMPLES

4.1 24-pulse transformer for a railway DC supply

The first application example deals with the 24-pulse DC supply of a railway substation. The corresponding circuit is represented in Fig. 3.

The DC supply is made of two 12-pulse transformers parallel connected. Each of them is modeled by using 15 linked inductors. The first transformer has the connection Dd11.75d0.75 and the second one has the connection Dd0.25d11.25. The parallel connection allows supplying the 4 diode rectifiers with shifted angles –22.5°, -7.5°, +7.5° and +22.5°. This leads to a 24-pulse rectifier system. Note that the rectifiers are parallel connected. To equalize the load of both 12-pulse transformers, additional chokes are connected in the DC-link. The next figures present simulation results in steady state at 100% load with symmetrical transformers, as calculated in point 2.

As expected, the first dominant AC supply phase current harmonics are the 23^{rd} and the 25^{th}. The harmonics analysis results confirm the proposed 24-pulse modeling.

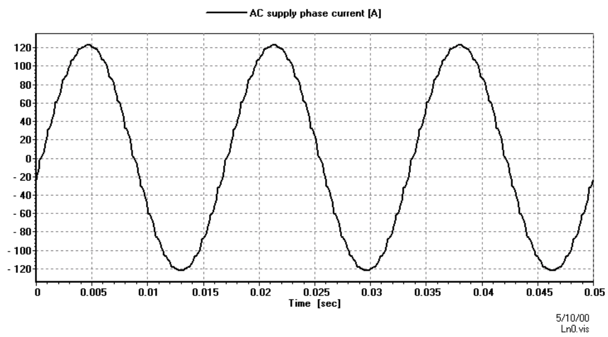

Figure 4 - AC supply phase current.

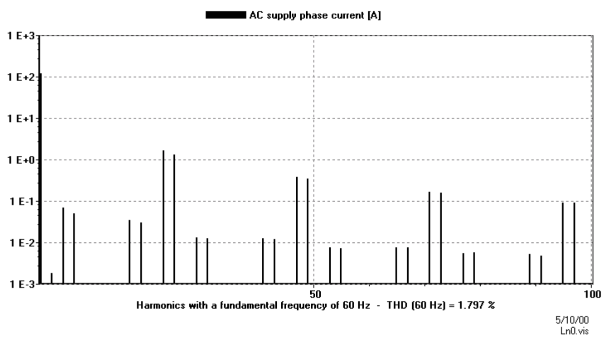

Figure 5 - Spectrum of AC supply phase current.

4.2 Multi-level Voltage Source Inverter 18-pulse DC supply

The studied circuit (see Fig. 6) corresponds to a multi-level Voltage Source Inverter (VSI) feeding an AC motor. This topology has been presented in [5].

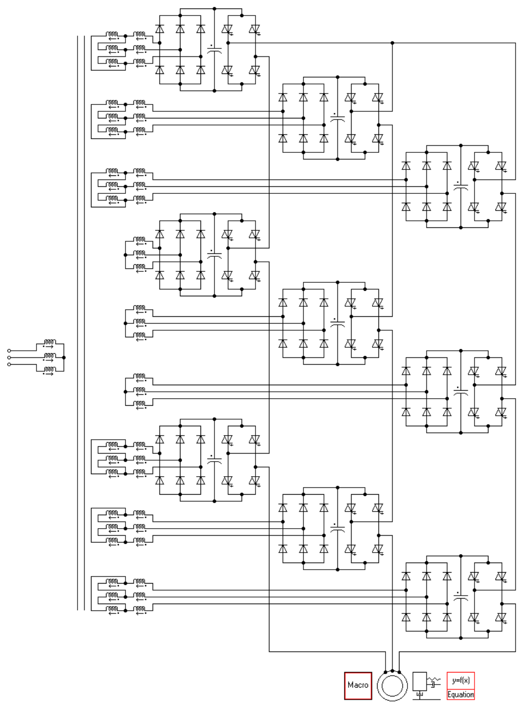

Figure 6 - 18-pulse DC supply for multi-level VSI.

The VSI is made of several DC-cells, each supplied through a 6-pulse diode rectifier. Regarding the present paper, the most interesting part of the above topology is the 18-pulse multi-winding transformer. The VSI requires many floating voltage potentials. A special transformer having many output or secondary windings fulfills this specification.

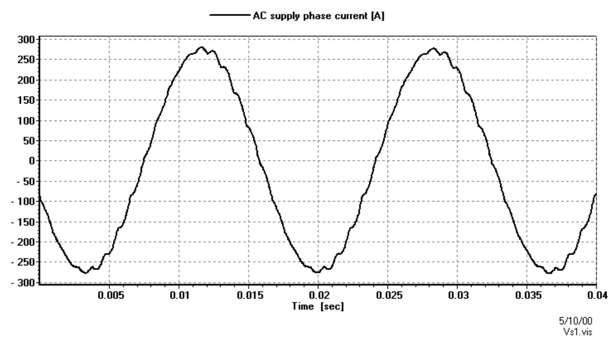

Figure 7 - AC supply phase current.

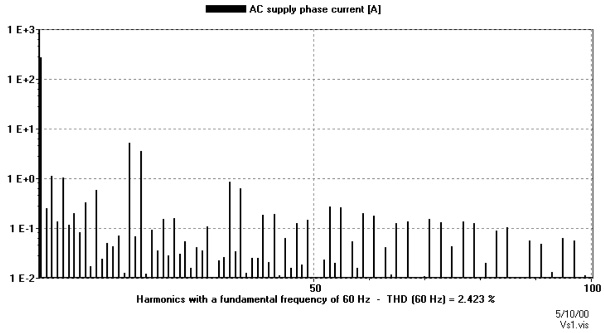

Figure 8 - Spectrum of AC supply phase current.

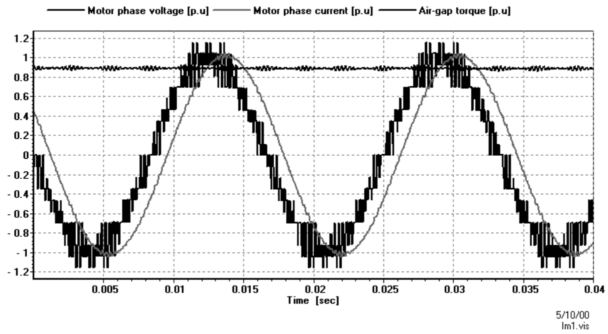

Figure 9 - Motor phase voltage, current and air-gap torque

The transformer is modeled using 48 linked inductors. Each linked inductor is coupled with the 47 other linked inductors. The calculation of all the needed parameters is based on the same principle as the one developed in point 2. As expected, the first dominant AC supply phase current harmonics are the 17^{th} and the 19^{th}. The simulation results have been compared successfully with measurements coming from [4].

5 CONCLUSIONS

Multi-winding phase shifting transformers are a suitable solution to supply DC systems with low harmonics content in the AC supply phase current. Based on a real example, a modeling methodology has been developed. This method requires the main data of the transformer, the phase shifting angles as well as the windings connections. Multi-winding phase shifting transformers have been simulated using the *SIMSEN* simulation software, which proved to be a powerful tool to simulate such complex transformers. Harmonics analysis of simulation results (elimination of low order harmonics 5, 7, 11, 13) has validated the proposed methodology.

REFERENCES

[1] A. Sapin, J.-J. Simond: SIMSEN : A modular software package for the analysis of power networks and electrical machines, CICEM'95, Hangzhou, China.

[2] J.-J. Simond, A. Sapin, B. Kawkabani, D. Schafer, M. Tu Xuan, B. Willy: Optimized Design of Variable Speed Drives Based on Numerical Simulation, EPE 1997.

[3] Paice D.: Power Electronic Converter Harmonics, Multipulse methods for clean power, IEEE Press.

[4] Enjeti P.N, Choi, S., I.J. Pitel : Polyphase Transformer Arrangements with Reduced kVA Capacities for Harmonic Current Reduction in Rectifier-Type Utility Interface, IEEE Trans. on Power Electronics, Vol. 11, No. 5, Sept. 1996.

[5] Peter W. Hammond: A New Approach to Enhance Power Quality for Medium Voltage AC Drives, IEEE Transaction on Industry Applications, Vol. 33 No 1, 1997.

[6] A. Sapin, P. Allenbach, J.-J. Simond: Modeling of Multi-Winding Phase Shifting Transformers, Applications to DC Supplies. ICEM 2000, Helsinki