Using Zigzag Transformers with Phase-shift to reduce Harmonics in AC-DC Systems

H. K. Høidalen, R. Sporild

Abstract-- In large industry production facilities, twelve pulse rectifier units are often used for the conversion to DC-current. In order to improve the harmonic signature from the plant versus the grid, several transformer units are internally phase-displaced by means of combined couplings involving Z-arrangement. This paper outlines how such a transformer is modelled in ATP both as a Saturable Transformer component and as a coupled RL-matrix. An actual industrial plant with 5 12-pulse rectifying units in parallel is modelled with 6º phase displacement. The analysis of the harmonic content of the supplying current shows that this arrangement is equivalent to a 60-pulse system only in the case of perfect symmetry in the system. Measurements show that the 3rd, 5th , 7th, 11th, and 13th harmonics easily exceed the theoretical 59th and 61st harmonics.

Keywords: Saturable transformer, melting furnace, diode rectifiers, harmonics, phase-shift, zigzag, test report, ATPDraw.

I. Nomenclature

The zigzag winding is characterized by the following parameters:

- U_1 Voltage across the two winding parts
- U_{1z} Voltage across the z-part
- U_{1y} Voltage across the y- part
- n Ratio between U_{1y} and U_{1z}
- α Phase-shift related to a Y-winding
- L_{1z} Inductance in the z-part in [H] or [pu]
- R_{1z} Resistance in the z-part in [Ω] or [pu]
- L_{1y} Inductance in the y-part in [H] or [pu]
- R_{1y} Resistance in the y-part in [Ω] or [pu]

II. Introduction

In the power supply to large industrial plants involving AC-DC converters, power quality is a problem. The current on the AC-side contains harmonics of the order $k \cdot n \pm 1$, where k is the number of pulses in the rectifying bridge and n=1, 2… Filters on the high voltage AC side are expensive and alternative solutions are often beneficial. When several AC-DC converters are installed in parallel, power transformers with different phase-shifts can be used to cancel out the harmonic currents. In a particular industrial plant in Sunndalsøra-Norway five 12-pulse AC-DC converters are installed in parallel with phase shifts -12º, -6º, 0º, +6º, and +12º, which results in an equivalent 60-pulse system.

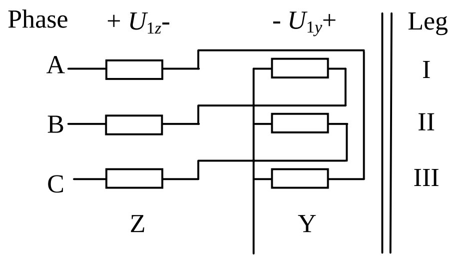
A zigzag coupling on the primary side and two secondary sides with 30 degrees internal phase shift supplying a 12-pulse rectifying bridge is investigated in this paper. The modeling of zigzag transformers with the saturable transformer components in ATP [1] is reported in [2, 3]. In the present paper the analysis in [2] is extended to the case of an arbitrary phase shift of <-60,0> and <0,60> degrees based on [4].

III. Modeling of Zigzag Winding

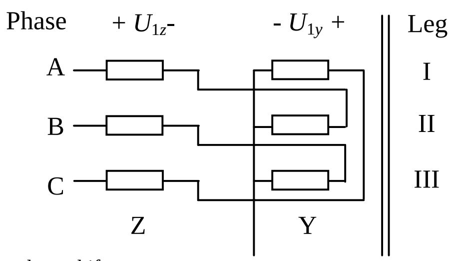
In this section the zigzag winding is modeled both according to the saturable transformer component in ATP and as a more general coupled RL-matrix formulation.

A. *Zigzag winding basics*

Two basic zigzag couplings are used for negative and positive phase shifts as shown in fig. 1.



a) Negative phase shift



b) Positive phase shift

Fig. 1 Investigated zigzag couplings.

For negative phase shifts the zigzag winding of phase A consists of one part on leg I and one part on leg III in the opposite direction. The total voltage of phase A, U_1 is shown in fig. 2.

H. K. Høidalen is with The Norwegian University of Science and Technology, Dept. of Electrical Power Engineering, N-7491 Trondheim, Norway (e-mail: hans.hoidalen@elkraft.ntnu.no).

R. Sporild is with ABB AS Norway, Automation Technologies Division, P.O.Box 6540 Rodeløkka, N-0501 Oslo, Norway (e-mail: roald.sporild@no.abb.com).

Presented at the International Conference on Power Systems Transients (IPST'05) in Montreal, Canada on June 19-23, 2005
Paper No. IPST05 - 44

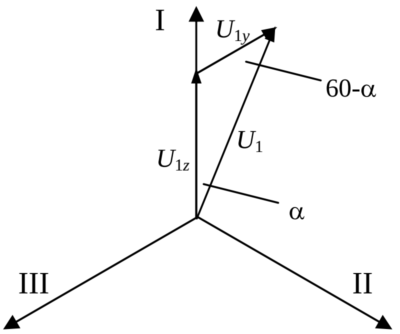


Fig. 2 Voltages of the zigzag winding of phase A. Negative phase shift.

The absolute values of the phase voltages of each winding part are

$$n = \left|\frac{U_{1y}}{U_{1z}}\right| = \frac{\sin(\alpha)}{\sin(60-\alpha)} \tag{1}$$

$$|U_{1z}| = \frac{|U_1|}{\cos(\alpha) + n\cdot\cos(60-\alpha)} \tag{2}$$

$$|U_{1y}| = \frac{|U_1|\cdot n}{\cos(\alpha) + n\cdot\cos(60-\alpha)} \tag{3}$$

with α equal to the absolute value of the phase shift.

The voltage vectors are

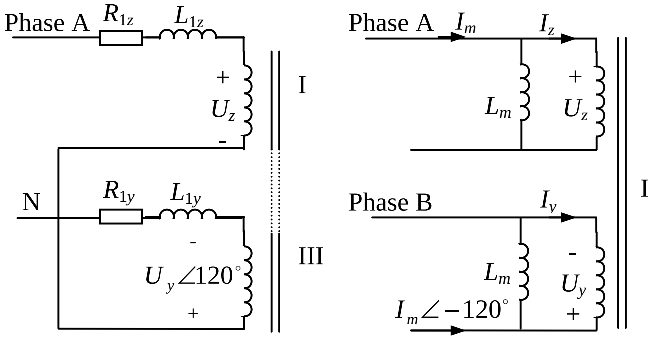
$$U_{1z} = \frac{U_1}{1+n\cdot\angle-60^\circ} \text{ and } U_{1y} = \frac{U_1\cdot n\angle-60^\circ}{1+n\cdot\angle-60^\circ} \tag{4}$$

The same equations apply to the positive phase shift case.

B. The Saturable Transformer approach

This section outlines how to model a zigzag winding compatible with the saturable transformer model in ATP [1]. The short circuit and magnetizing characteristics are handled along with the zero-sequence behavior.

The winding resistance, the leakage inductance, and the magnetizing impedance of the total zigzag winding are now divided in two parts as illustrated in fig. 3.



a) Short circuit b) Open circuit

Fig. 3 Distribution of the short-circuit and open-circuit impedances. Positive sequence, negative phase shift.

The total short-circuit resistance and inductance as obtainable from measurements are $R_1 = R_{1z} + R_{1y}$ and $L_1 = L_{1z} + L_{1y}$ respectively as shown in fig. 3a). The winding resistance is proportional to the number of windings turns while the leakage inductance is proportional to the square of this number. Since the winding voltages U_z and U_y are proportional to the number of turns this gives $R_{1y} = n\cdot R_{1z}$ and $L_{1y} = n^2\cdot L_{1z}$. As a result

$$R_{1z} = \frac{R_1}{1+n} \quad \wedge \quad R_{1y} = \frac{R_1\cdot n}{1+n} \quad [\Omega] \tag{5}$$

$$L_{1z} = \frac{L_1}{1+n^2} \quad \wedge \quad L_{1y} = \frac{L_1\cdot n^2}{1+n^2} \quad [\mathrm{H}] \tag{6}$$

The total magnetizing impedance as obtainable from measurements is $Z_m = U_1 / I_m$. According to fig. 3b) the magnetizing current in the two winding parts is

$$I_m = \frac{U_{1z}}{Z_{mz}} + I_z \quad \wedge \quad -I_m\angle-120^\circ = \frac{-U_{1y}}{Z_{my}} + I_y \tag{7}$$

When the transformer is unloaded $I_z + I_y\cdot n = 0$. From this (7) can be reformulated as

$$I_m\cdot(1-n\angle-120^\circ) = \frac{U_{1z}}{Z_{mz}} - n\cdot\frac{U_{1y}}{Z_{my}} \tag{8}$$

Inserting (4) into (8) gives after some manipulation

$$I_m = \frac{U_1}{1+n+n^2}\cdot\left(\frac{1}{Z_{mz}} - \frac{n^2\angle-60^\circ}{Z_{my}}\right) \tag{9}$$

The magnetizing inductance is proportional to the square of the number of windings, $L_{my} = n^2\cdot L_{mz}$. If the magnetizing impedance is assumed to be purely inductive the total measurable apparent magnetizing inductance is $L_m = |U_1/(j\omega I_m)|$, where U_1 is the phase voltage. The absolute value is taken since a phase shift in the magnetizing current will be introduced in the zigzag winding. From (9) the magnetizing inductances in each winding part are obtained

$$L_{mz} = \frac{L_m\cdot|1-\angle-60^\circ|}{1+n+n^2} = \frac{L_m}{1+n+n^2} \tag{10}$$

$$L_{my} = \frac{L_m\cdot n^2}{1+n+n^2} \tag{11}$$

In the saturable transformer model in ATP a magnetizing branch is added to the primary winding only. In this case Z_{my} in (9) must be set to infinity. This results in

$$L_{mz}^{ATP} = \frac{L_m}{1+n+n^2} \tag{12}$$

The zero sequence reluctance can similarly to the magnetizing inductance be found from fig. 3b). In this case the current $I_0 = I_m$ in phase B on leg I is equal in amplitude, but opposite in phase to the current in phase A. This also applies to voltages across the two winding parts, so that $U_{y0} = -n \cdot U_{z0}$ and $U_{z0} + U_{y0} = U_{10}$. The relationship $I_{z0} + I_{y0} \cdot n = 0$ is still valid. This gives

$$
\begin{aligned}
&I_0 = \frac{U_{z0}}{Z_{0z}} + I_{z0} \quad \wedge \quad -I_0 = \frac{-U_{y0}}{Z_{0y}} + I_{y0} \Rightarrow \\
&I_0(1-n) = \frac{U_{10}}{1-n} \cdot \left(\frac{1}{Z_{0z}} + \frac{n^2}{Z_{0y}} \right)
\end{aligned}
\tag{13}
$$

The zero sequence impedance is mostly inductive and for a 3-leg core mostly linear. The zero sequence inductance is proportional to the square of the number of windings. This gives

$$
L_{0z} = \left| \frac{U_{10}}{\omega \cdot I_0} \right| \cdot \frac{2}{(1-n)^2} \ \wedge \ L_{0y} = \left| \frac{U_{10}}{\omega \cdot I_0} \right| \cdot \frac{2 \cdot n^2}{(1-n)^2} \tag{14}
$$

The saturable transformer component in ATP supports only a zero-sequence reluctance in the primary winding. In this case Z_{0y} is infinite and

$$
L_{0z}^{ATP} = \left| \frac{U_{10}}{\omega \cdot I_0} \right| \cdot \frac{1}{(1-n)^2} \tag{15}
$$

The reluctance specified in ATP is $R_0 = U^2 / 3L_0$ where U is the voltage across the winding where the reluctance is connected. This gives

$$
R_0 = \frac{U_{z0}^2}{3 \cdot L_{0z}^{ATP}} = \frac{\omega \cdot |I_0 \cdot U_{10}|}{3} \tag{16}
$$

The Saturable transformer formulation for zigzag windings is supported directly by ATPDraw 4 [3].

C. Coupled RL-Matrix Formulation

The zigzag transformer can also be modeled as coupled inductance and resistance matrices based on the standard star equivalent in the per unit system as shown in fig. 4.

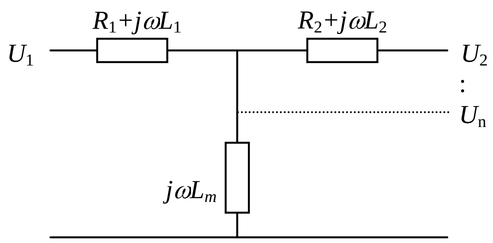


Fig. 4. Basic Star-equivalent

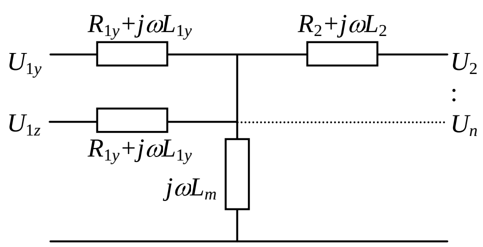


Fig. 5a. Modified Star-equivalent, positive sequence

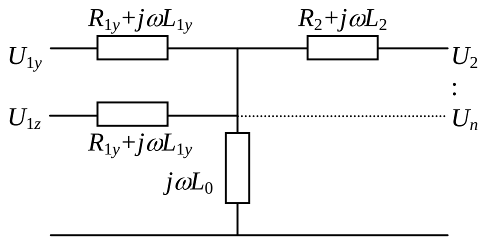


Fig. 5b. Modified Star-equivalent, zero sequence

The zigzag impedances in fig. 5 are calculated from (5) and (6) scaled by the square of the voltage ratios to obtain a common per unit basis. This gives with R_1 and L_1 in [pu]:

$$
\begin{aligned}
R_{1z} &= \frac{R_1}{1+n} \cdot \frac{U_1^2}{U_{1z}^2} = \frac{R_1 \cdot (1+n+n^2)}{1+n} \quad [pu] \\
R_{1y} &= \frac{R_1 \cdot n}{1+n} \cdot \frac{U_1^2}{U_{1y}^2} = R_{1z} / n \quad [pu]
\end{aligned}
\tag{17}
$$

$$
\begin{aligned}
L_{1z} &= \frac{L_1}{1+n^2} \cdot \frac{U_1^2}{U_{1z}^2} = \frac{L_1 \cdot (1+n+n^2)}{1+n^2} \quad [pu] \\
L_{1y} &= \frac{L \cdot n^2}{1+n^2} \cdot \frac{U_1^2}{U_{1y}^2} = L_{1z} \quad [pu]
\end{aligned}
\tag{18}
$$

The formulation of inductance and resistance matrices will be outlines here, since this is the approach used by SIMSEN [4]. From the modified per unit star-equivalents in fig. 5 the inductance matrices in positive and zero sequence systems are

$$
L_P = \begin{bmatrix} L_{1y} + L_m & L_m & L_m & \cdots \\ L_m & L_{1z} + L_m & L_m & \cdots \\ L_m & L_m & L_2 + L_m & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{19}
$$

$$
L_Z = \begin{bmatrix} L_{1y} + L_0 & L_0 & L_0 & \cdots \\ L_0 & L_{1z} + L_0 & L_0 & \cdots \\ L_0 & L_0 & L_2 + L_0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{20}
$$

The total inductance matrix is

$$
L = \begin{bmatrix} L_{1zT} & L_x & L_x & \cdots \\ L_x & L_{1yT} & L_x & \cdots \\ L_x & L_x & L_{2T} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{21}
$$

The resistance matrix is diagonal with equal zero and positive sequence parameters

$$
R_P = R_Z = \begin{bmatrix} R_{1z} & 0 & 0 & \cdots \\ 0 & R_{1y} & 0 & \cdots \\ 0 & 0 & R_2 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{22}
$$

Each matrix element in (21) and (22) consists of a 3x3 sub-matrix on the standard form

$$Z_{ij} = \begin{bmatrix} Z_S & Z_M & Z_M \\ Z_M & Z_S & Z_M \\ Z_M & Z_M & Z_S \end{bmatrix} \tag{23}$$

with $Z_{Sii} = \frac{1}{3} \cdot (Z_{Zii} + 2Z_{Pii})$ and $Z_{Mij} = \frac{1}{3} \cdot (Z_{Zij} - Z_{Pij})$

The on- and off-diagonal elements in (21) are

$$L_{iT} = \frac{1}{3} \cdot \begin{bmatrix} 3L_i + 2L_m + L_0 & L_0 - L_m & L_0 - L_m \\ L_0 - L_m & 3L_i + 2L_m + L_0 & L_0 - L_m \\ L_0 - L_m & L_0 - L_m & 3L_i + 2L_m + L_0 \end{bmatrix} \tag{24}$$

$$L_x = \frac{1}{3} \cdot \begin{bmatrix} L_0 + 2L_m & L_M & L_0 - L_m \\ L_0 - L_m & L_0 + 2L_m & L_0 - L_m \\ L_0 - L_m & L_0 - L_m & L_0 + 2L_m \end{bmatrix} \tag{25}$$

To obtain the final inductance and resistance matrices each row and column in (21) and (22) are multiplied with the winding voltage and all elements are divided with the rated power as outlined in the EMTP TheoryBook [5].

IV. Case Study

This section outlines in details how to model a 3-winding transformer based on the test report and the result of using it to supply five 12-pulse rectifying bridges in parallel.

A. *Test Report*

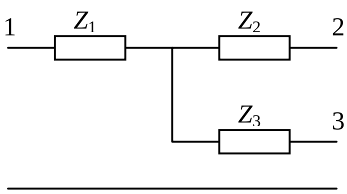
Table I shows the test report in the case of a -12º phase shift. Similar data appear for the other phase shifts (-6º, 0º, +6º, +12º). The short circuit resistances are very low and contain only one significant digit. This will introduce some inaccuracies in the calculations.

TABLE I
TEST REPORT DATA

Coupling:	ZN0d11yn0
Rated power:	115 MVA
Rated primary voltage:	85.92 kV
Rated secondary voltage Δ:	1.218 kV
Rated tertiary voltage Y:	1.230 kV
Rated frequency:	50 Hz
Open circuit current:	0.005 pu
Short circuit impedance 1-2:	0.004 + j0.085 pu
Short circuit impedance 1-3:	0.004 + j0.085 pu
Short circuit impedance 2-3:	0.01 + j0.158 pu
Phase shift Z (ref. 3):	-12 deg.

The standard per unit equivalent circuit for the short circuit impedances is shown in fig. 6.

Table II shows the calculated winding voltages, resistances and leakage inductances based on (2-3) and (5-6). These values are used directly in the Saturable Transformer component of ATP. The secondary and tertiary voltages are not exactly equal and this will introduce the 6·(2n-1)±1 harmonics. The difference is due to the very low number of turns (<10) on the DC sides. This is partly compensated by transducers located between the transformer and rectifier. Since only 6 digits are available in the ATP-format for the values in Table II the resistances must be specified with care as shown in fig. 7.



$$Z_1 = (Z_{12} + Z_{13} - Z_{23})/2 = -0.001 + \mathrm{j}0.006 \text{ [pu]}$$
$$Z_2 = (Z_{12} + Z_{23} - Z_{13})/2 = 0.005 + \mathrm{j}0.079 \text{ [pu]}$$
$$Z_3 = (Z_{13} + Z_{23} - Z_{12})/2 = 0.005 + \mathrm{j}0.079 \text{ [pu]}$$

Fig. 6 Per unit equivalent circuit

TABLE II
TRANSFORMER EQUIVALENT, PHASE SHIFT -12 º

Winding	U [kV]	R [mΩ]	L [mH]
1z	73.73	-50.2	1.136
1y	20.64	-14.0	0.0891
2D	2.11	0.193	0.00973
3Y	1.23	0.066	0.00331

If the HV winding 1 is chosen as the primary winding, the magnetizing branch will be added to the first winding part (Z) of the zigzag winding. Alternatively the magnetizing branch should be added to the low-voltage Y-coupled winding. This could be done externally or by choosing winding 2 or 3 as the primary. The magnetizing branch added to winding 1 should be calculated from (12). The measured inductance is

$$L_m = \frac{1}{2\pi \cdot 50 \cdot 0.005} \text{ pu} = 0.637 \text{ pu}$$
$$= 0.637 \cdot (85.92 \text{ kV})^2 / 115 \text{ MVA} = 40.9 \text{[H]}$$

and the inductance that should be added to winding 1Z in ATP:

$$L_{mz}^{ATP} = \frac{L_m}{1 + n + n^2} = 30.1 \text{[H]}$$

As a starting point the zero-sequence inductance L_0 is set to zero. This corresponds to an infinite zero-sequence reluctance, ref. (16) and fig. 5b. In fig. 7 a 3-leg core is checked and this enables the Transformer Three Phase model in ATP. However, when the zero-sequence reluctance R0 is infinity this is equivalent to the standard Saturable Transformer component.

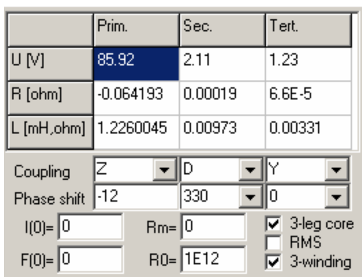


Fig. 7. Data input in to the Saturable transformer model in ATPDraw. The magnetization is specified as *i*= 1A and λ=30.1 Wb-T.

B. Comparison between the Saturable Transformer and the RL-Matrix Formulation

The matrix formulation results in a 12x12 coupled RL-matrix. The input impedance of the high voltage side is calculated as a function of frequency and the absolute value is shown in fig. 8. The impedances of the two types of models are practically identical. As the frequency approaches zero all the impedances will reach the negative resistance -0.064 Ω. This is not a physically correct result however, and is due to the artificial star-point introduced in the models as shown in of fig. 4-5. Instability as discussed in [6] due to the negative resistance was not observed in this study. An alternative to the two equivalent types of models is the admittance approach used in BCTRAN [1, 5]. As long as the test report only gives information about the total zigzag winding (with phase shift) it is not straight forward to avoid the negative impedance. An argument against the RL-matrix formulation is that the accuracy is limited by the large difference between magnetizing and short circuit inductances [5]. To reduce this problem, high resolution (16 digits) is used in this study. The accuracy is in this case not a problem compared to the Saturable transformer model with only 6 digits available for the short circuit impedances.

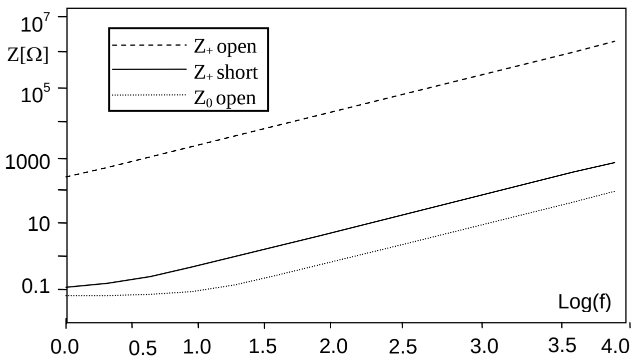


Fig. 8. Input impedance at the high-voltage side (zigzag) of the transformer models, phase shift -12º. Open and short circuit positive sequence and open circuit zero sequence.

C. Simulation of five parallel 12-pulse rectifying groups

This example is based on a practical situation in an industrial plant in Norway. Five 12-pulse rectifying (diode) groups are installed in parallel as shown in fig. 9. From the 132 kV side the 5 units are supplied by regulating transformers feeding the rectifying transformers and adjusted to 132/82.5 kV for nominal load. Three situations are simulated and the harmonic content of the phase current on the 132 kV side is calculated

- without phase-shift between the five transformers, Ydy
- with a 6º phase shift between the five (0º, ±6º, ±12º), Zdy
- same as above, but the secondary voltage is adjusted from 1.218 to 1.23 kV, Zdmy

Figure 10 shows that 5 phase shifting transformer units in parallel reduce the content of the 12n±1 harmonics up to 2 decades. The 6·(2n-1)±1 harmonics are much less reduced. Adjusting the secondary voltage from 1.218 to 1.23 kV to obtain perfect symmetry between the secondary and tertiary windings will have a significant effect on all 6n±1 harmonics up to 59 and 61 resulting in an equivalent 60 pulse system.

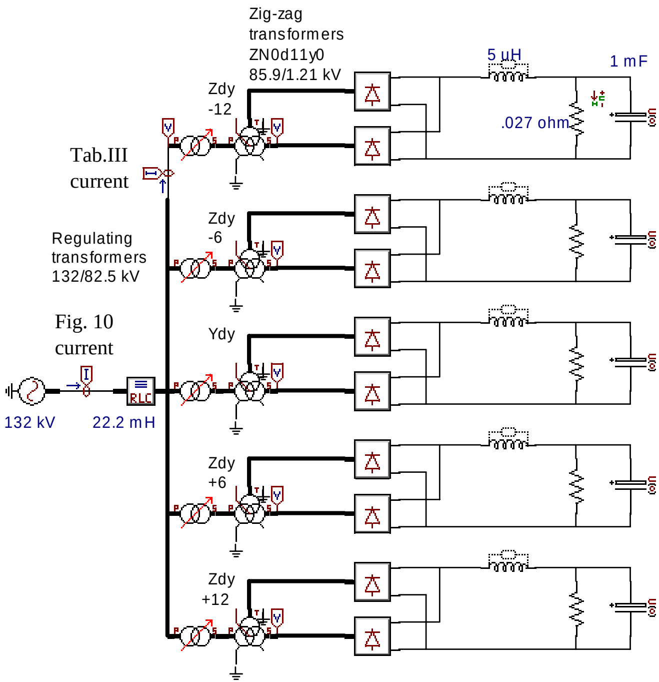


Fig. 9. Circuit in ATPDraw for simulation of five parallel 12-pulse rectifying groups. The transformer with 0º phase shift is coupled Ydy. The nominal DC current and voltage from each rectifier is 55 kA and 1.5 kV. The snubbers of the diode rectifiers are set to C=9 µF in series with R=1.5 Ω with reference to [7]. The regulating transducers between transformer and rectifier ignored.

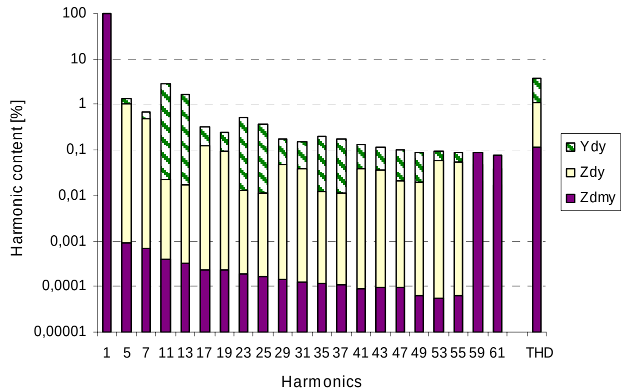


Fig. 10. Harmonic content of the primary side current, phase A in [%]. Obtained by PlotXY[8]. Ydy: no phase shift, Zdy: 6º phase shift, Zdmy: 6º phase shift and adjusted secondary voltage from 1.218 to 1.23 kV. All other harmonics than those shown in fig. 10 are insignificant. Time step Δt=1 µs.

The industry process in fig. 9 allows the loss of up to 2 rectifying groups. The total harmonic distortion (THD) increases from the nominal value 1.13 % to 1.72 % and 2.79 % when one and two groups are disconnected, respectively before regulation of the applied voltage.

V. COMPARISON WITH MEASUREMENTS

The current on the 132 kV side into rectifier group 1 (-12º phase shift) was also measured. The regulating transformers were adjusted to a 132/52 kV ratio resulting in 0.94 kV and 55 kA in the 0.017 Ω DC load. The filters were disconnected during the measurements. Table III shows substantial differences between the measurements and the calculation, except for the most important 11th and 13th harmonics. The 1st and the 3rd harmonics are higher in the measurements while the 5th and 7th harmonics are higher in the calculations. The THD is measured as 5.74% and calculated as 6.56 %. The content of 2nd and 3rd harmonics obtained from the measurements can originate from the 132 kV supply, but these harmonics are typically caused by saturation effects ignored in the simulations. Also nonlinearities in the current transformers used in the measurements can cause lower order harmonics. The lower content of 5th and 7th harmonics in the measurements can be due to the regulating transducer on the secondary side ignored in the simulations.

TABLE III
CALCULATED AND MEASURED HARMONICS OF 132 KV SIDE CURRENT INTO RECTIFYING GROUP 1 IN [A]RMS .

Harm.	Meas.	Calc.
1	266.3	246.8
2	0.47	0.00
3	1.53	0.00
4	0.30	0.00
5	3.03	5.89
7	1.90	3.29
9	0.50	0.00
11	12.17	12.33
13	8.17	7.32
15	0.27	0.00
17	0.80	1.13

Harm.	Meas.	Calc.
19	0.60	0.86
23	1.00	2.01
25	0.90	1.48
29	0.00	0.68
31	0.00	0.58
35	0.43	0.84
37	0.53	0.67
41	0.20	0.44
43	0.10	0.38
47	0.10	0.36
49	0.00	0.30

VI. CONCLUSIONS

Modeling of zigzag transformers using the SATURABLE TRANSFORMER component in ATP and a general coupled RL-matrix formulation is presented in this paper. Formulas for the ratios of voltage, resistance and leakage inductance between the two parts of a zigzag winding are presented. Magnetization and the zero-sequence are briefly outlined. The two types of models have identical characteristics in the frequency domain. The saturable transformer approach is well suited for standard modeling and a nonlinear magnetizing branch can easily be added (scaled as in (12)). The matrix formulation enables a more sophisticated zero-sequence modeling.

An example shows how to obtain a model for a three-winding transformer with zigzag on its primary. The example shows how five parallel 12-pulse rectifying groups become an equivalent 60-pulse system seen from the HV-side when a phase shift of 6º is introduced between five perfectly balanced zigzag coupled transformers. Changes from the ideal balanced situation will rapidly introduce 3rd, 5th, 7th, 11th, and 13th harmonics, however. The results confirm a considerable reduction in THD due to the phase-shift arrangement. This in turn contributes to a simplified and cheaper filter arrangement as compared to the ordinary 12-pulse converters.

Comparing calculations to measurement shows substantial deviations. Only the most significant harmonics can be predicted accurately. Detailed modelling of the voltage supply, transformer magnetization, regulating mechanisms, and the DC load characteristics is required to calculate the other harmonics with accuracy.

VII. REFERENCES

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VIII. BIOGRAPHIES

Hans Kristian Høidalen was born in Drangedal, Norway in 1967. He received the M. S. and PhD degrees from the Norwegian Institute of Technology in 1990 and 1997, respectively. He is now an associate Professor at the Norwegian University of Science and Technology. His special field of interest is computation of electromagnetic stresses.

Roald Sporild was born in Trondheim, Norway in 1965. He received the M. S. degree from the Norwegian Institute of Technology in 1990. He is now engaged by ABB AS Norway as an Senior Electrical Engineer performing power system calculations.