

Measurement of Circulating Currents in Split-Winding Transformer and Comparison with Numerical Calculation

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Abstract—Split-winding transformer is a one of the common transformer types with one low-voltage winding placed above the other low-voltage winding and with the jointly high-voltage and regulation winding. The paper investigates circulating currents that occur in high-voltage and regulation windings in case of nonsymmetric load. In addition, measurement of circulating currents for a case of 240MVA, 220 kV transformer is presented along with a numerical calculation of circulating currents and compared with the measurement.

Index Terms—Power transformer, split-winding, circulating currents.

I. INTRODUCTION

One of the common multi winding topologies used in power transformers are two low-voltage windings placed one above the other with shared high-voltage winding, known also as split-winding transformers. This kind of transformers are typically used as step-up transformers in power generation systems. With a symmetrical load on both low-voltage windings, split-winding transformers behave entirely like a standard transformer [1]. However, when the load of low-voltage windings is not symmetrical, or in extreme situation, when only one low-voltage winding is loaded, circulating currents will occur in the high-voltage winding. If there is a regulation winding on the high-voltage side, circulating currents will flow also through each regulation winding. Reason for the circulating current occurrence is a magnetic link – a mutual inductance between the windings, and the fact that all the windings on the high-voltage side are electrically connected. Figure 1 shows the principles of circulating current generation. In the case of connection only the upper low-voltage winding, there comes the disbalance of the stray flux. The stray flux of upper low-voltage winding grasps the lower part of the high-voltage winding and induces circulating current in the high-voltage winding loop. This current superposes with the regular current in the upper part of high-voltage winding and appears isolated in the lower part. The same cause of circulating current applies for additional regulation branches in the high-voltage section. In some cases, circulating current can have an opposing direction to the regular current and the regular current of winding is then reduced.

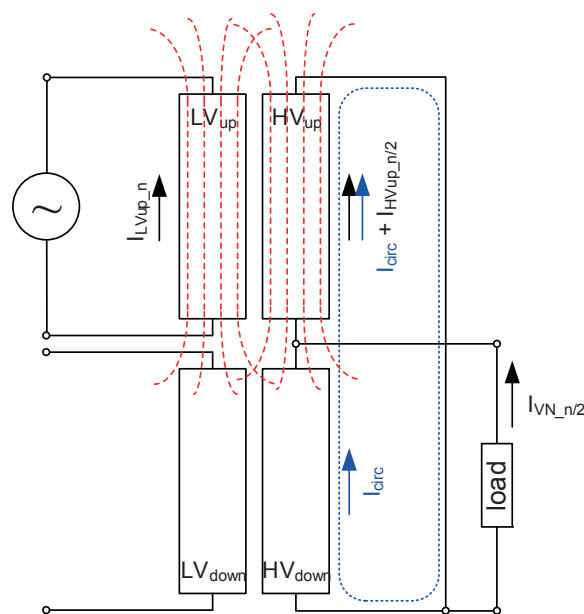


Figure 1: Principle of circulating currents occurrence.

The consequences of circulating currents are increased ohmic and eddy losses in windings, higher stray flux and stray losses amount, changed impedance voltage [2] and higher forces so the transformer has to be designed to withstand higher demands [3][4]. Circulating currents can be avoided in split-winding transformers by using two separate tap changers, the one for upper part and the one for the lower part of regulation winding as this solution would eliminate electrical connection between upper and lower high-voltage and regulating winding, but with a cost of two tap changers. This paper will present detailed measurement of circulating currents for a case of a 240 MVA and 220 kV step-up transformer. Circulating currents are measured in every turn of regulation winding for every tap position as well as in high-voltage winding. Transformer was simulated with FEM model and the calculated results are compared with measurement [5].

II. TRANSFORMER DESCRIPTION

The transformer used for the measurement is a three-phase transformer with three-leg core with nominal power of 240 MVA and nominal voltage 220 kV. It has one regulation winding, reversing type, split on the upper and the lower half. Measurement was conducted with the active part outside of the tank with reduced voltage. This doesn't have an impact on the percentual amount of circulating currents because they depend solely on winding's geometry and winding's mutual inductances.

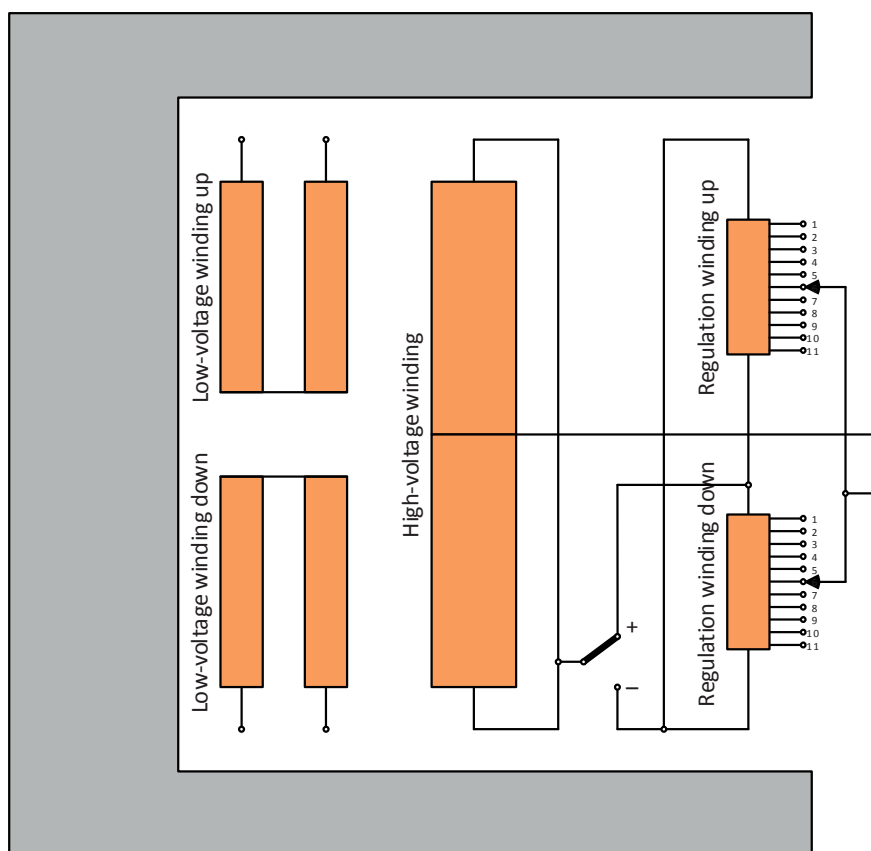


Figure 2: Block scheme of transformer winding and connections.

Every turn of upper part of the regulation winding is connected to the related turn of lower part of regulation winding with a copper bar. Circulating currents are measured on the bars with appropriate equipment.

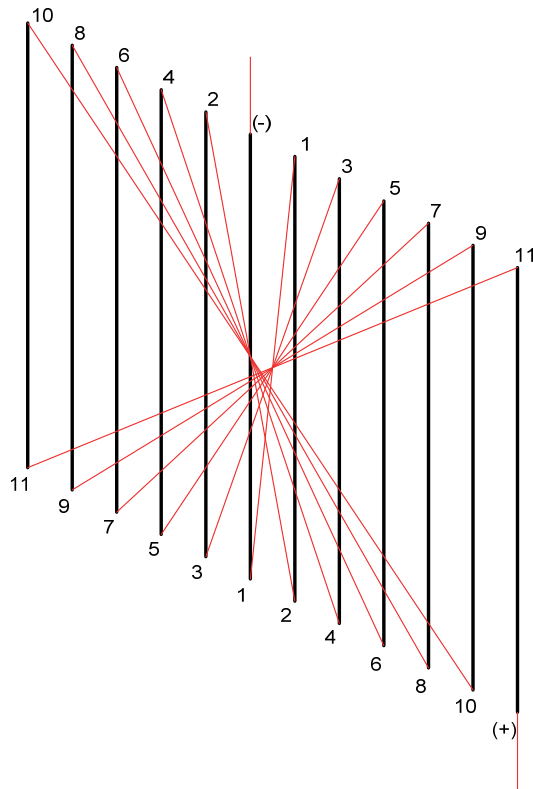


Figure 3: Connections of turns of one part (upper or lower) of regulation winding.

III. MEASUREMENTS DESCRIPTION

The measurement of circulating currents was conducted in the test bay of Končar Power Transformers. Transformer's high-voltage winding was connected to the motor-generator setup. The generator induced 10% of the nominal transformer voltage. Nominal voltage wasn't possible to use because the active part of the transformer was out of tank and oil which is the main insulator and cooling agent and also due to personnel safety. Since circulating currents depend on mutual inductance of windings, current percentage doesn't influence the phenomena. Currents were measured with Fluke true RMS current clamp model 325. For each tap change, voltage was decreased to zero and increased back to 10% of the nominal voltage.

IV. MEASUREMENTS RESULTS

The Table I shows circulating currents in high-voltage winding measured for every tap position. In some cases, circulating current has the same direction as the regular current (positive values) and sometimes has the opposing direction (negative values). An average value of circulating current between upper and lower part of the high-voltage winding is taken as the valid value.

TABLE I. CIRCULATING CURRENTS IN HIGH-VOLTAGE WINDINGS RELATIVE TO THE REGULAR CURRENT.

tap	1 (+)	2 (+)	3 (+)	4 (+)	5 (+)	6 (+)	7 (+)	8 (+)	9 (+)	10 (+)	11 (+)
HV	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HV up	8.8%	8.2%	7.5%	6.8%	6.2%	5.7%	4.8%	4.4%	3.5%	2.9%	2.5%
HV down	9.0%	8.4%	7.5%	7.0%	6.4%	5.9%	5.1%	4.7%	3.8%	3.3%	2.5%
HV average	8.9%	8.3%	7.5%	6.9%	6.3%	5.8%	5.0%	4.5%	3.6%	3.1%	2.5%

tap	12 (K)	13 (0)	14 (-)	15 (-)	16 (-)	17 (-)	18 (-)	19 (-)	20 (-)	21 (-)	22 (-)
HV	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HV up	1.8%	1.5%	0.6%	-0.1%	-0.7%	-1.4%	-2.4%	-2.7%	-3.2%	-4.0%	-4.5%
HV down	1.9%	1.2%	0.7%	-0.4%	-0.8%	-1.4%	-2.0%	-2.8%	-3.3%	-4.1%	-4.5%
HV average	1.9%	1.4%	0.7%	-0.3%	-0.8%	-1.4%	-2.2%	-2.7%	-3.2%	-4.1%	-4.5%

The Table II shows the amount of circulating current relative to the regular current for every turn of the regulation winding and for every position of the tap changer. Since the circulating currents have the opposing direction to the regular current, values are negative. In the table there is a separation between the turns of the regulation winding with the regular current (black color) and the turns without the regular current (red color). Even if the tap changer is in such position that regular current cannot flow through the designated turn, that turn is electrically connected with the corresponding turn in the other half of regulation winding and circulating currents can flow in that loop.

TABLE II. CIRCULATING CURRENTS IN THE TURNS OF REGULATION WINDINGS RELATIVE TO THE REGULAR CURRENT FOR DIFFERENT TAP POSITIONS; NUMBERS IN BLACK ARE FOR THE TURNS WITH REGULAR CURRENT, AND NUMBERS IN RED FOR THE TURNS WITHOUT REGULAR CURRENT.

tap ->	1 (+)	2 (+)	3 (+)	4 (+)	5 (+)	6 (+)	7 (+)	8 (+)	9 (+)	10 (+)	11 (+)
T-	-32.9%	-32.3%	-32.2%	-31.8%	-31.1%	-30.8%	-30.3%	-29.9%	-29.8%	-29.3%	-28.9%
T1	-86.4%	-36.2%	-36.3%	-35.4%	-35.5%	-34.5%	-34.1%	-34.0%	-33.5%	-32.7%	-32.5%
T2	-78.9%	-78.7%	-28.2%	-28.2%	-27.8%	-27.4%	-27.2%	-26.7%	-26.3%	-26.1%	-25.7%
T3	-89.9%	-89.4%	-89.4%	-38.7%	-39.0%	-38.0%	-37.3%	-37.4%	-37.0%	-36.4%	-36.1%
T4	-73.7%	-73.8%	-72.9%	-73.2%	-22.2%	-22.3%	-21.9%	-22.1%	-21.3%	-21.5%	-21.1%
T5	-93.2%	-92.9%	-92.7%	-92.2%	-92.2%	-42.1%	-42.1%	-41.3%	-40.9%	-40.1%	-39.8%
T6	-72.4%	-72.1%	-71.8%	-71.8%	-71.0%	-71.7%	-20.5%	-20.9%	-20.0%	-20.3%	-19.7%
T7	-91.6%	-91.8%	-92.1%	-92.0%	-92.0%	-91.9%	-91.7%	-47.2%	-47.0%	-46.0%	-45.8%
T8	-65.6%	-65.7%	-65.3%	-65.1%	-64.9%	-65.2%	-64.6%	-65.3%	-19.1%	-19.4%	-18.6%
T9	-79.7%	-80.2%	-80.6%	-81.0%	-81.3%	-81.7%	-81.9%	-82.3%	-81.9%	-53.1%	-53.3%
T10	-62.2%	-62.0%	-61.6%	-61.9%	-61.3%	-62.1%	-61.3%	-61.6%	-61.1%	-62.8%	-31.2%
T11	-58.8%	-59.4%	-59.6%	-60.1%	-60.5%	-61.3%	-61.5%	-62.1%	-62.3%	-63.1%	-62.5%

tap ->	12 (K)	13 (0)	14 (-)	15 (-)	16 (-)	17 (-)	18 (-)	19 (-)	20 (-)	21 (-)	22 (-)
T-	-28.6%	-22.8%	-23.1%	-23.5%	-23.9%	-24.5%	-24.5%	-24.9%	-25.4%	-25.8%	-26.1%
T1	-31.5%	-31.8%	-19.9%	-19.2%	-20.2%	-20.5%	-20.6%	-21.1%	-21.7%	-22.0%	-22.3%
T2	-25.9%	-25.5%	-25.5%	-26.5%	-26.3%	-26.8%	-26.8%	-27.4%	-27.6%	-28.1%	-28.3%
T3	-35.6%	-35.3%	-34.8%	-35.3%	-16.8%	-16.6%	-16.8%	-17.7%	-18.3%	-18.5%	-19.3%
T4	-21.2%	-20.6%	-20.5%	-19.9%	-20.2%	-31.2%	-30.7%	-31.4%	-31.5%	-31.9%	-32.1%
T5	-39.4%	-39.1%	-38.3%	-38.2%	-37.4%	-37.9%	-13.6%	-13.8%	-15.0%	-15.1%	-15.8%
T6	-19.6%	-19.1%	-19.1%	-18.8%	-18.8%	-17.9%	-18.6%	-33.4%	-33.2%	-34.0%	-33.8%
T7	-45.2%	-44.5%	-43.9%	-43.5%	-42.7%	-42.6%	-41.9%	-42.2%	-9.9%	-9.9%	-11.0%
T8	-18.6%	-18.5%	-18.3%	-17.8%	-17.9%	-17.4%	-17.5%	-16.7%	-17.0%	-36.2%	-35.4%
T9	-52.3%	-51.6%	-50.7%	-50.1%	-49.4%	-48.9%	-48.1%	-48.0%	-47.0%	-47.4%	-5.9%
T10	-30.6%	-30.3%	-29.9%	-28.8%	-28.3%	-28.1%	-28.7%	-27.2%	-26.9%	-26.3%	-27.1%
T11	-59.4%	-59.0%	-58.1%	-57.2%	-56.4%	-56.1%	-55.1%	-54.8%	-53.9%	-53.6%	-52.2%

V. MEASUREMENT ANALYSIS

Figure 4 shows circulating currents in high-voltage winding relative to the regular current. When displayed in a chart, circulating currents shows linear dependence to the tap position. When tap changer deactivates one by one turn of the regulation winding, then comes to (0) position and then activates one by one turn with the opposing polarity, mutual inductance conjunction of high-voltage winding is changing gradually. The chart is not symmetrical regarding percentage of circulating currents because transformer's windings don't have the same distance to the upper and lower yoke due to different insulating distance. This is the cause of different mutual inductance conjunction for terminal tap positions.

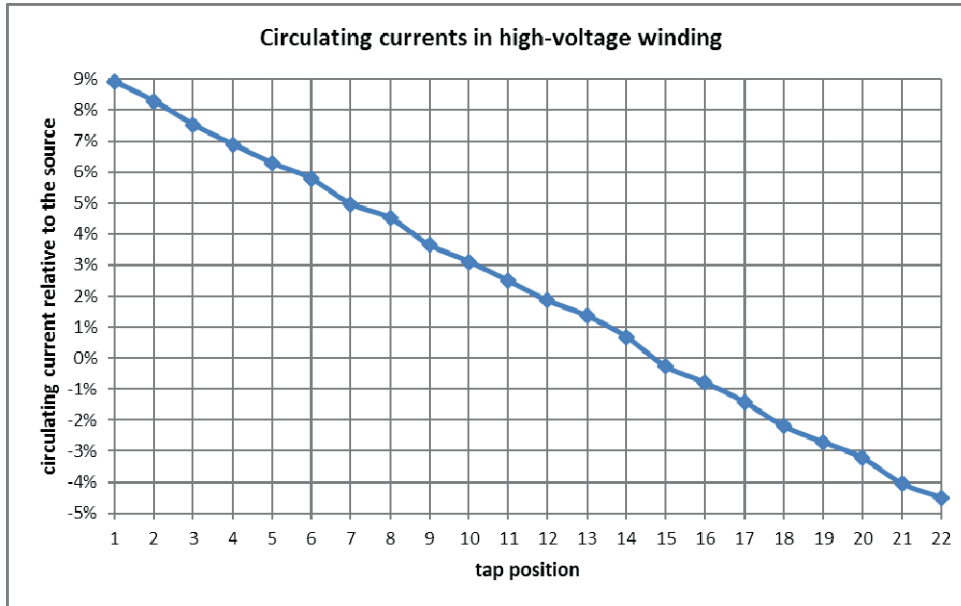


Figure 4: Circulating currents in high-voltage winding relative to the regular current.

Due to different geometry of regulation winding (for every tap position there is always equal number of turns active in the upper and the lower part), circulating current have different dependence to the tap positions. Percentage value of circulating current in individual turn is almost independent to the tap position (Figure 5 and 6). However, the amount of circulating current dramatically differ from turn to turn. For that reason, the Table III and Figure 7 show circulating currents in the turns of regulation windings relative to the regular current; average for all tap positions and grouped in (+) tap positions, no current and (-) tap positions.

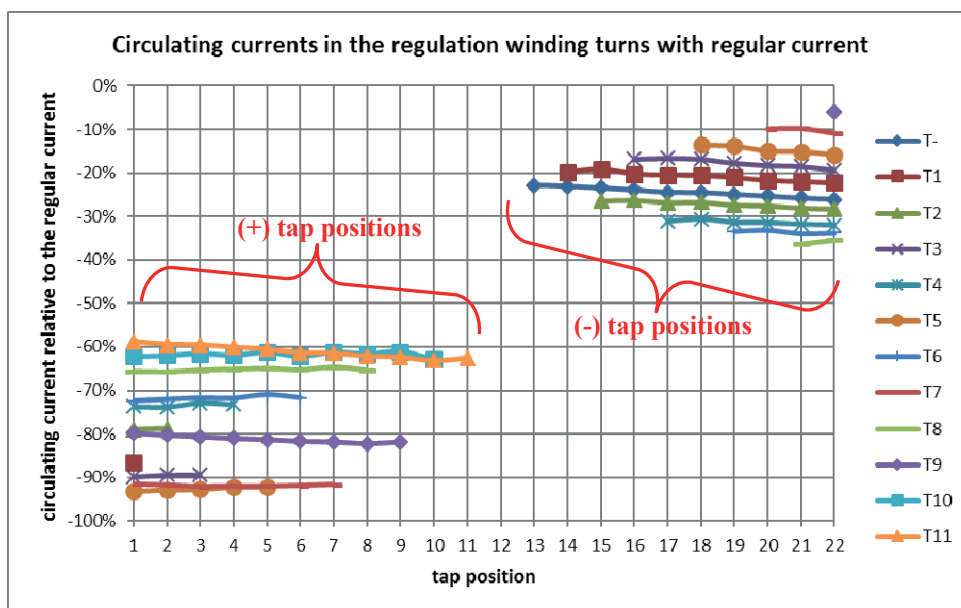


Figure 5: Circulating currents in the turns of the regulation winding with regular current relative to the regular current.

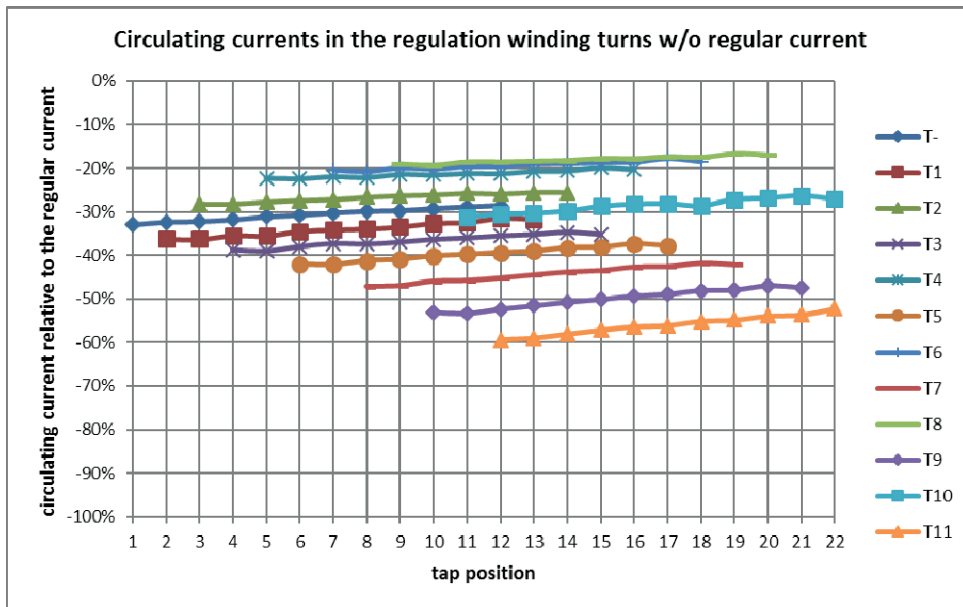


Figure 6: Circulating currents in the turns of the regulation winding without regular current relative to the regular current.

TABLE III. CIRCULATING CURRENTS IN THE TURNS OF REGULATION WINDINGS RELATIVE TO THE REGULAR CURRENT; AVERAGE FOR ALL TAP POSITIONS AND GROUPED IN (+) POSITIONS, NO REGULAR CURRENT AND (-) POSITIONS.

turn	average (+)	no regular current	average (-)
T-		-30.9%	-24.4%
T1	-86.4%	-34.5%	-20.8%
T2	-78.8%	-27.1%	-26.9%
T3	-89.6%	-37.5%	-17.7%
T4	-73.4%	-21.8%	-31.5%
T5	-92.6%	-41.1%	-14.7%
T6	-71.8%	-20.3%	-24.7%
T7	-91.8%	-46.5%	-10.2%
T8	-65.2%	-19.0%	-35.8%
T9	-81.2%	-53.2%	-5.9%
T10	-61.8%	-31.2%	
T11	-61.0%	-56.0%	

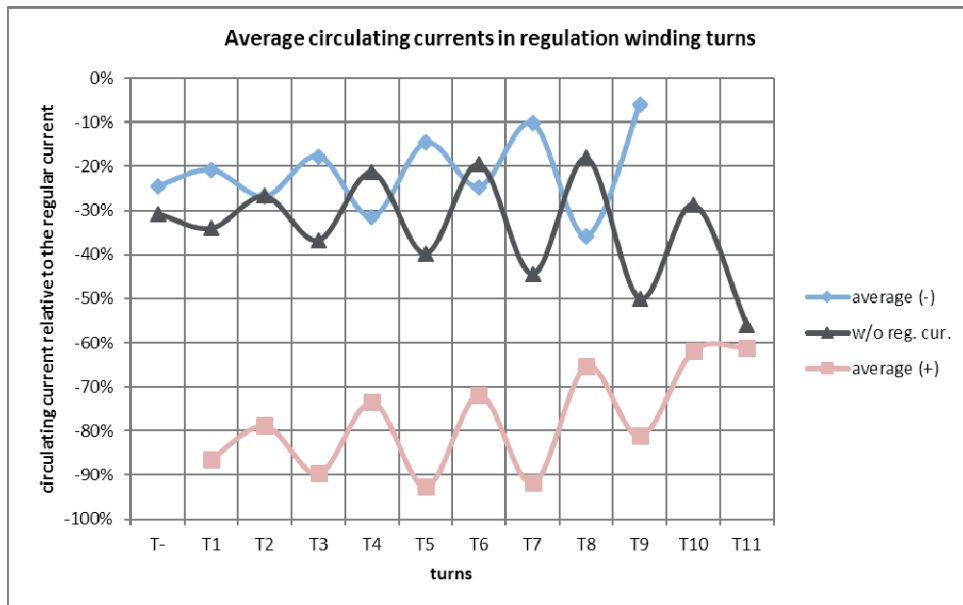


Figure 7: circulating currents in the turns of regulation windings relative to the regular current; average for all tap positions and grouped in (+) positions, no current and (-) positions.

VI. NUMERICAL CALCULATION

For the purpose of showing principles of numerical calculation of circulating currents here is presented 2D FEM model with simplified regulation winding. The model was calculated with Ansys Maxwell in magnetic transient mode. The model is 2D rotational symmetry with linear material properties. Winding blocks electrical connection is defined through associated electrical scheme, which is the integral part of the model. Regulation winding is represented as one block for upper part and one block for lower part of the winding. This approach can give good results for terminal tap positions where all or almost all the turns of the regulation winding carry regular current. For intermediate tap positions each turn and its associated electrical scheme has to be modeled individually.

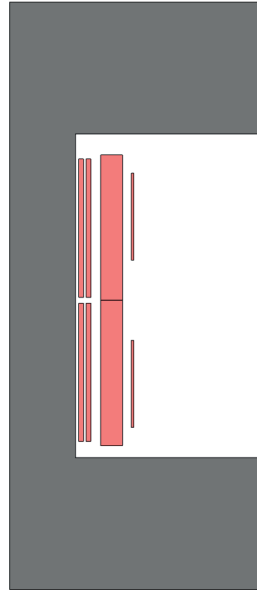


Figure 8: 2D FEM model for circulating current calculation.

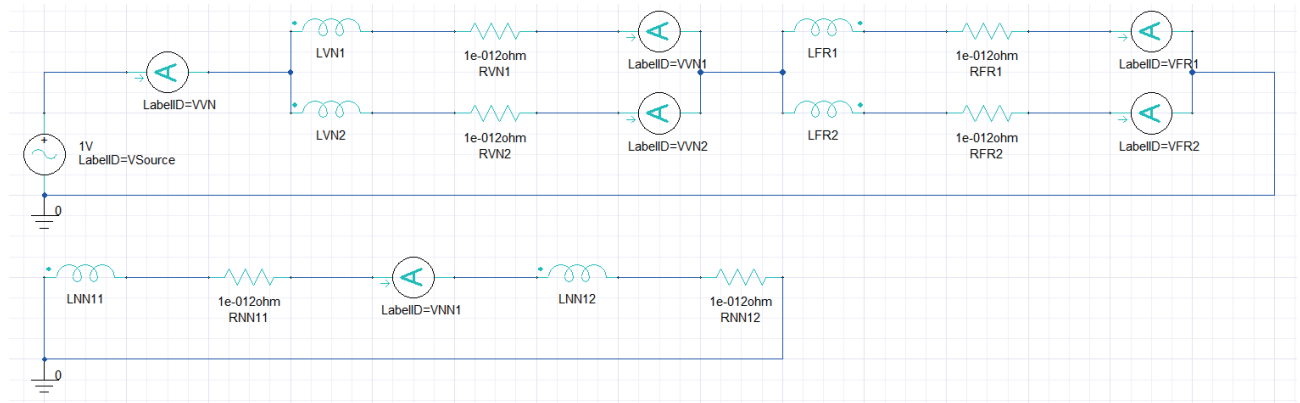


Figure 9: electrical connection of windings in 2D FEM model for circulating current calculation.

TABLE IV. CALCULATED AND MEASURED CIRCULATING CURRENTS IN THE HIGH-VOLTAGE AND REGULATION WINDINGS RELATIVE TO THE REGULAR CURRENT FOR TERMINAL TAP POSITIONS.

tap position	HV calculated	HV measured	regulation w. calculated	regulation w. measured
1 (+)	8.2%	8.9%	-89.0%	-86.4%
22 (-)	-5.1%	-4.5%	-16.4%	-26.1%

For the sake of comparison in the Table IV there are calculated average measured circulating currents for the tap positions 1 ((+) position) and 22 ((-) position). The Table IV shows very good agreement for the tap position 1 and acceptable agreement for the tap position 22.

VII. CONCLUSION

Circulating currents occur in split-winding transformers in the cases of asymmetrical load of upper and lower low-voltage windings. Circulating currents flow in the loops of high-voltage and regulation windings. This paper presents comprehensive measurements of circulating currents on the 240 MVA and 220 kV step-up transformer. Circulating currents are measured in upper and lower part of high-voltage and regulation windings for every tap position and every turn of regulation winding. Measurement analysis shows that for this type of transformer circulating currents in high-voltage winding linearly depend on the tap position. However, for the regulation winding it was shown that circulating currents in winding's turns are practically independent to tap position and can be grouped in three groups: (+) tap positions, no current and (-) tap positions where circulating currents depend solely on the physical location of the turn. Finally, a numerical calculation of circulating currents was presented. Numerical calculation is carried out with 2D FEM model with associated electrical scheme. It is shown that modeling windings as blocks can be used with satisfactory precision for calculation of circulating currents for terminal tap position where all or almost all the turns of the regulation winding carry regular current, while for intermediate tap positions each turn and its associated electrical scheme has to be modeled individually.

VIII. REFERENCES

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