High frequency modeling of Transformer winding for fault diagnostics using FEM solver.

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Abstract— High frequency modeling is essential in the design of power transformers, to study the impulse voltage distribution, winding integrity and insulation diagnosis. Circuit models of interlinked inductances and capacitance have been widely used to analyze the transformer transients caused by lightning or switching surges. A winding model applicable to higher frequencies is required in order to analyze the effect of very fast transients (VFT) due to the surges originated in gas insulated switchgear (GIS).

The extraction of winding parameters for the healthy transformer is really useful to compare the frequency response of the healthy transformer to the currently used one. An improved procedure is proposed here, in which the circuit parameters are evaluated on turn-to-turn basis directly from the physical dimensions of transformer winding. The parameters of transformer winding are extracted using FEM package (ANSOFT).

Keywords- High frequency modeling, very fast transients, frequency response, FEM package

1. Introduction

The high frequency contents of power transients due to fast breakers and power electronics make high frequency models of various power system components necessary in order to assess the risk of unexpected component failure. The use of fast vacuum breakers instead of sf6 breakers due to environmental aspect is an example of a possible source of very fast transients. Transformers are an example of a component, of which the internal voltage distribution under transient voltage application can only be determined from a detailed high frequency model.

Lumped circuit models have been commonly used to analyze the transformer transient associated with the lightning or switching surges in the lumped model, the winding is divided into a number of parts usually into coil sections pairs. This is insufficient to calculate the influence from the disconnecting switching surges or the very fast transient over voltages generated in GIS. For this kind of frequency analysis, the parameter calculated from the winding geometry are used to modeling the transformer as a network of lumped r, l, c elements which are computed with the fem package (ANSOFT) software on the basis of manufacturer data(geometry, materials). Power transformer model has been subject of investigation and research for a century. Several proposed methods use simplified examples/cases in the elaboration process, and in many cases the methods are not very well suited for real transformers.

Using FEM to establish the elementary parameters of a lumped parameter model for real transformers is in principle easy assuming constructional details of the transformer are available. However to avoid a huge, unsolvable problem, equivalent materials must be obtained based on analytical calculations.

All parameters such as losses (dielectric, proximity and iron losses), self and mutual inductance and capacitance are calculated from the geometry and material parameters, making his method effective for real transformer geometries.

2. Modeling the Geometry

The method described is based on a linear lumped parameter-description using self- and mutual inductances as shown in Fig.
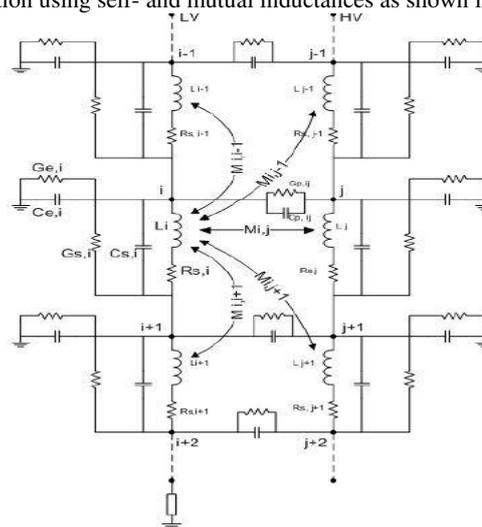
Figure 1. A lumped equivalent circuit of transformer winding

3. Parameter Calculation

The basis for the representation of the frequency-dependent phenomena is the principle of complex permeability. The penetrations of magnetic field into iron laminates and winding strands are highly frequency-dependent. Field equations are solved analytically in order to determine the averaged field reaction and bulk losses. The iron core and copper winding is then replaced by an equivalent, isotropic material with a complex frequency-dependent permeability as shown in Fig. . This equivalent material has the same external/global behavior as the original material. The elements of the system matrices RLCG are calculated by FEM for each frequency-point. Calculation based on vector potential and complex flux results in a fast computation but a poor accuracy since solution is a result of an integral across very few finite elements. A better approach for the computation of these elements is based on the energy. Self inductance and resistance is calculated applying current in the element .Dielectric parameters (C & G) are calculated in generally the same manner as the magnetic parameters, using the electrostatic energy. The resistive losses consist of several different contributions

Ohmic/DC-losses, Skin-effect losses, Proximity-effect losses,

Iron core losses. The three last contributions are eddy-current losses. Use Proximity- and core-losses are represented by the complex permeability, while skin-effect is handled analytically by modifying the diagonal elements of the R and L matrices. Resistive losses are mainly dominated by the core losses, and the total losses computed for the first element for the chosen frequency-distribution.

4. Extracting winding circuit parameters using FEM field solver.

In order to study the transient behavior of transformer through high frequency modeling, accurate method of computing the parameters become necessary. Hence the R, L, and C is computed using (electrostatic, magneto static, eddy current solver) FEM based algorithm. The calculation of a transformer capacitance is fundamental for predicting the frequency behavior of the device. At high frequencies the capacitive effect is being more. The capacitive parameter of the transformer winding can be calculated using$_S$ electrostatic computation method in FEM field solver.
Governing equation:

The electrostatic field simulation computes static electric fields arising from potential differences and charge distributions. It solves for the electric potential (x, y) in the field equation:

$$\nabla(\varepsilon r\ \varepsilon 0\ \nabla\phi(X,Y))=0 \qquad (1)$$

$\phi(X, Y)$ = Electric potential
εr = Relative permittivity
$\varepsilon 0$ = permittivity of free space,

This equation is derives from Gauss's law, which indicate that the net electric flux passes through any closed surface is equal to the net positive charge enclosed by that surface. After the solution for the potential is generated, the system automatically computes the E field and d field using the relation $e=-\nabla\phi$ and $D=\varepsilon 0\varepsilon r\ E$.

Capacitance represents the amount of energy stored in the electric field in and around the structure. In a single circuit the capacitance represent the amount of stored energy in the electric field that arises due to the voltage difference across the dielectricTo compute the capacitance using this method, field and D field associated with a given distribution of voltage must first be computed. The electrostatic field simulator, which compute the electric potential at all points of the problem region, perform this task.

To compute the capacitance matrix for a structure, the MAXWELL 2D field simulator performs a sequence of electrostatic field simulations.

5. Transformer under analysis:

Effect of electric field along the z direction remains unchanged. We can neglect the z coordinate and thus the problem to become two dimensional problems. For the transformer the LV winding is taken for the reference

Type of winding : Spiral
Turns/Layer : 17
Turns/Coil : 34
Axial height : 369 mm
Radial depth : 19.5 mm
Conductor : 9.5*3.5/0.4 mm
Inter layer : 3mm

Figure 2. Single turn representation of winding

The voltage distribution on the transformer LV winding is shown.

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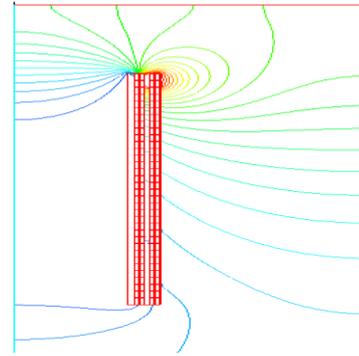
Figure 3: Voltage distribution of Capacitance model.

The capacitance matrix of the transformer LV winding shown below,

.0518	-.0402	-9.43	-50.12	-30.46	-20.56	-20.02	-10.06	-10.3	-10.11
-.0402	.0906	-.039	-60.16	-20.90	-10.81	-1.029	-90.87	-70.82	-60.38
-90.40	-.0396	.089	-0.039	-50.90	-20.70	-10.60	-10.18	-90.08	-70.14
-50.20	-60.18	-.034	0.089	-30.90	-50.84	-50.84	-50.84	-50.84	-50.84
-30.46	-20.90	-50.94	-0.039	.089	-20.70	-20.70	-20.70	-90.08	-70.08
-25.86	-18.10	-20.70	-50.84	-.039	.0909	-.040	-40.13	-25.10	-45.10
-20.20	-90.80	-10.60	-25.10	-50.17	-.036	.0908	-.012	-10.16	-35.12
-16.10	-70.84	-10.18	-15.80	-26.60	-20.10	-20.16	.0907	-24.16	-20.16
-13.30	-60.34	-90.08	-70.10	-40.16	-25.10	-40.16	-40.16	.0907	-.0469
-10.11	-50.28	-70.14	-80.10	-50.14	-40.10	-45.16	-50.14	-40.16	.0906

Table 1.Capacitance Matrix

The magneto static field simulator computes magnetic fields arising from DC current and

other sources like permanent magnets and external magnetic fields. . The magneto static field simulator solves for the magnetic vector potential in the field equation

$$Jz(x, y) = \nabla*(1/\mu r\mu o)\ (\nabla*Az(x, y)) \qquad (2)$$

$Az(x, y)$ = component of the magnetic vector potential
$Jz(x, y)$ = DC current density
μr = relative permeability of each material
μo = permeability of free space

After the z component of A is computed, the flux density B and agnetic field H can be computed

using the relationship $B=\nabla XA$ and $H=1/\mu o\mu rB$. Both B and H lie in the xy cross section being analyzed Inductance can be calculated from the energy stored in the magnetic field when the current flows.

$$U = (1/2)\ L\ I^2 \qquad (3)$$

Where U= energy stored in the magnetic field
L=inductance
I=current flowing in the circuit

The Maxwell 2D field simulator computes inductance associated with a structure by simulating the magnetic field that arises when varies voltages and current are applied. Then, by computing the energy stored in those field, it can then compute the necessary inductances

To compute the inductance using this method, the B field and the H field associated with a distribution of currents must first be computed. The magneto static field simulator, which computes the magnetic vector potential at all points in the problem region, perform this task.

Inductance can be calculate in the following way

1. Inductance in terms of flux linkage and current.
2. Inductance in terms of voltages and time varying currents

To compute an inductance matrix, the Maxwell 2D field simulator performs a sequence of magneto static field simulations. The energy stored in the system

$$U_{ij} = (1/2) \, L \, I^2 \qquad (4)$$

The flux lines on the surface of the transformer LV winding are shown below.
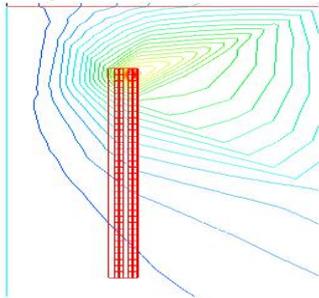
Figure 4: Magnetic field distribution on transformer LV winding.

The inductance matrix of the transformer LV winding show below, The inductance values are in micro henry.

	1	2	3	4	5	6	7	8	9	10
1	20.9	19.50	13.08	11.10	900.2	724.1	581.0	462.1	367.1	293.1
2	19.5	20.89	14.10	11.14	922.1	736.1	586.1	461.1	411.1	341.1
3	13.0	20.70	20.78	14.14	462.1	691.1	729.1	574.1	4521	340.1
4	11.1	11.12	14.12	29.60	14.14	14.12	400.1	245.1	361.1	280.1
5	900	18.12	12.56	31.10	30.16	24.10	110.1	112.1	240.1	210.1
6	724	24.10	900.2	34.10	31.12	33.13	42.12	54.10	120.1	31.10
7	58.	28.12	700.1	700.2	900.1	36.12	34.20	42.10	36.12	25.10
8	46.	25.10	500.1	500.1	772.1	24.12	24.15	35.09	31.10	21.10
9	367	32.10	352.1	362.1	412.1	32.12	28.15	24.12	20.60	19.16
10	293	290.1	452.1	579.1	751.1	930.1	10.27	10.74	24.50	35.90

Table 2: Inductance Matrix

The eddy current field simulator assumes that the magnetic field and all other time varying quantities are stored as phasers, which can be visualized as a magnitude and phase or as a complex quantity. After specifying all AC current sources and all necessary boundary conditions, the system components the magnetic fields as follows. In conductors where eddy current occurs, H is calculated directly by:

$$\nabla \times (1/\sigma + J\omega\varepsilon \, \nabla \times H) = J\omega\mu H \qquad (5)$$

Or H is computed from the magnetic scalar potential ϕ:

$$\nabla \cdot (\mu\nabla\phi) = 0 \qquad (6)$$

Induce current allow magnetic field to penetrate conductors only to a certain depth, which is approximated by the formula:

$$\delta = (2/\omega\sigma\mu_o\mu_r)^{½} \qquad (7)$$

The AC magnetic field energy is given by

$$U_{AV} = 1/4 \int B.H^* \, dv \qquad (8)$$

Where H* is the complex conjugate of the magnetic field H. ohmic loss is used to compute the power loss in a structure, which is

$$P = \int j \cdot j^*/2\sigma \, dv \qquad (9)$$

Where j* is the complex conjugate of the current density j. Ohmic loss can also be expressed in terms of resistance and the total current:

$$P = R I_{rms}2 \qquad (10)$$

There fore the resistance is

$$R = p/I_{rms}2 \qquad (11)$$
$$= (1/2\sigma \int_v J.J^* \, dv)/I_{rms}2$$
$$R = (\int_v J.J^* \, dv)/(\sigma I_{peak}2) \qquad (12)$$

The magnetic flux lines for the LV winding in high frequency were extracted.
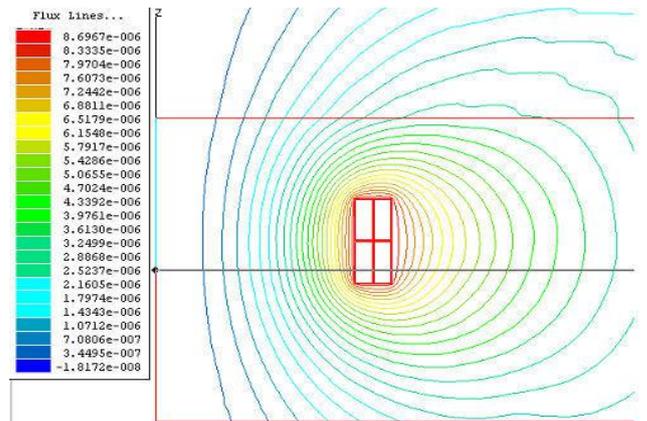
Figure 5: Magnetic field pattern on LV winding at high frequency

	1	2	3	4	5	6	7	8	9	10
1	1300	56.06	40.07	3.230	2.137	1.30	-.079	-1.12	-2.05	-2.08
2	56.06	1301	24.5	18.7	13.9	3.41	2.87	-2.37	-7.05	-10.96
3	40.07	24.5	1330	23.30	17.45	11.95	5.99	.151	-5.18	-9.54
4	3.230	18.7	2.87	1330	25.00	17.75	11.20	4.44	-1.96	-7.56
5	2.137	13.9	23.35	25.00	1331	26.23	17.90	10.30	2.85	-3.82
6	1.30	3.41	11.95	17.28	26.70	1330	26.90	17.61	19.20	1.52
7	-.079	2.87	5.99	11.25	17.40	26.90	1340	27.30	27.70	8.62
8	-1.12	-2.37	.151	4.44	10.30	17.64	27.32	1340	21.15	17.17
9	-2.05	-7.05	-5.18	-1.96	2.85	9.33	17.26	27.72	1340	22.45
10	-2.08	-10.96	-9.54	-7.54	-3.85	-5.52	8.66	17.17	17.41	1340

Table 3: Resistance Matrix

From eddy current solver, the resistance of the coil increases while increasing the frequencies.

From the FEM solver the Matrix are extracted and it's converted in to nodal form as shown in the figure 1.

Conclusion

The high frequency modeling of transformer winding is very useful for the analysis of transformer winding behavior under switching surges and lightning impulse. At high frequency, the transformer winding capacitance, inductance and resistance values are changed. From the geometrical data of the winding, the turn to turn transformer physical model was drawn and the R, L, C parametric matrix was evaluated using electrostatic, magneto static and eddy current solver.

The model takes into account of the frequency effect of the winding. The variation of the frequency using eddy current solver, the value of R is increases with respect to frequency. This physical meaning of the transformer will allow the identification of the problem inside the transformer. This parameter will be used for condition monitoring of the transformer. It will be useful for the detection of fault of the mechanical nature such as winding displacement.

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