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NETWORK SENSITIVITY ANALYSIS IN INSULATION FAULT MONITORING OF POWER TRANSFORMER

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ABSTRACT

Network function analysis is being developed for both the impulse test and monitoring of power transformer and offers advantage of fault identification and location. A three-phase equivalent circuit of power transformer based on the Bergeron method is introduced in this paper. The network sensitivities of two kinds of network functions are analyzed and compared in order to evaluate the insulation condition more efficiently. Grounding insulation faults with various intensities are simulated and the results show the potential contribution to insulation fault monitoring and location.

KEY WORDS: Bergeron method, network sensitivity, power transformer.

1. INTRODUCTION

Power Transformer insulation undergoes gradual ageing due to long-term operating electrical, thermal, mechanical, and chemical actions. The insulation malfunction of power transformers, especially main transformers, will lead to tremendous economical losses.

In the past two decades, several insulation monitoring techniques such as chromatogram analysis of transformer oil, partial discharge online monitoring, *tan* δ measurement and diagnosis based on expert system etc, have been introduced. They may have effects on the diagnosis of the whole condition of power transformer insulation, but they could not be able to locate insulation fault. In 1988, R. Malewski introduced a transfer function method in fault detection of power transformers [1] and made some progress in recent years. [2][3][4] In this method, the frequency-domain graphs deconvoluted from the test voltage and neutral current records were compared. Since no other mechanism could change the frequency of the local winding resonance with the increase in the applied test voltage, even a minor shift in the pole frequency of transfer function, which is one kind of network function, indicates a local breakdown.

In a qualitative sense, the sensitivity of a network is a measure of the degree of variation of its performance from nominal, due to changes in the elements constituting the network. Network sensitivity analysis has recently attracted much attention also in the field of analog circuits fault diagnosis and, in particular, of testability evaluation of linear circuits [5][6]. However, the network sensitivities are different corresponding to different network functions, and thus greatly influencing fault diagnosis and location of power transformers. In this paper, the differences between network sensitivities induced by different network functions are discussed and analyzed. A three-phase equivalent circuit of a transformer, which considers power losses and mutual inductances of transformer disks, is created for transient response calculations. When a fault appears in a power transformer, the parameters in the equivalent circuit will change, thus causing the changes of network functions, which provide a criterion to diagnose insulation malfunction. As an example, different network functions are simulated and the differences between corresponding network sensitivities are contrasted based on a 110kV/20MVA power transformer with SF_6 gas insulation. The conclusions are drawn at the end.

2. CALCULATION MODEL

A. Equivalent Circuit of Power Transformer

In the transient analysis of a transformer, different equivalent circuit forms correspond with different winding forms. For the disc winding, an equivalent circuit unit for a single disc, while for the interleaved winding, a unit for double discs.

The equivalent circuit of the three-phase transformer, considering the power loss and using double discs unit, is shown in Fig.1, in which r_k is the equivalent resistance of the unit k calculated from the structure parameters of the windings; C_{k0} is the ground capacitance of the unit k from the transformer's structure, mainly considering the coupling capacitance between the inner side of the HV windings and the outer side of the LV windings; C_{kk+1} is the longitudinal equivalent capacitance calculated from

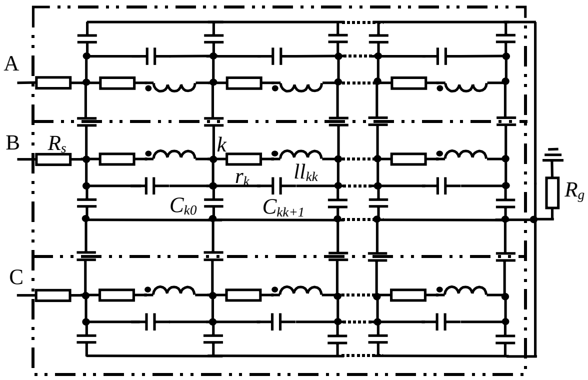


Fig.1. Equivalent circuit

the turn-to-turn geometric capacitance and disc-to-disc geometric capacitance by equal total energy converting theory[7];ll_{kk} is the self-inductance of the double discs; in addition, ll_{kj} is the mutual inductance between unit k and j which is not marked in Fig.1. In a rapid transient condition, the flux lines tend to center around the conductors rather than penetrating into the iron core and for high frequency components of surges the iron acts effectively as an earthed boundary [8] and thus its effect can be neglected approximately. The self and mutual inductances will be reduced somewhat because of the skin effect during the high frequency transient. For a single-turn air-core coil, the measured inductance at 500kHz is about 10% lower than that at 100Hz and at a higher frequency is close to 10% due to the flux lines saturation [9]. Thus the calculated inductance parameters can be reduced by about 10% of parameters of the air core coil.

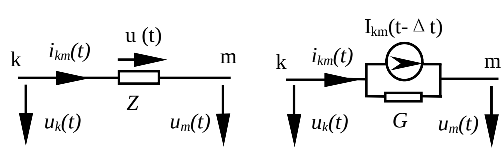
B. Bergeron Method

In Bergeron method, an independent power line with distributive parameters and an inductance L as well as capacitance C with lumped parameters is equivalent to a calculation circuit of resistance characteristics, namely a Norton circuit consisting of an equivalent resistance G and a current source I_{km} paralleled as drawn in Fig.2. The relationship between the voltage and the current of an independent inductance branch, for an example, can be expressed in integral form as

$$i_{km}(t) - i_{km}(t-\Delta t) = \frac{1}{L}\int_{t-\Delta t}^{t} u(t)dt$$

(1)

where Δt is the time step. From the trapezoidal integration principle, (1) can be given as



(a) Component with lumped parameter

(b) Equivalent Circuit

Fig.2. Calculation circuit of Bergeron Method

$$i_{km}(t) = \frac{\Delta t}{2L}[u_k(t) - u_m(t)] + i_{km}(t-\Delta t) + \frac{\Delta t}{2L}[u_k(t-\Delta t) - u_m(t-\Delta t)]$$

(2)

Independent resistance, capacitance and current source branch can be dealt with in the same way and then the branch current of each can be attained in the same form as

$$i_{km}(t) = G\cdot[u_k(t) - u_m(t)] + I_{km}(t-\Delta t)$$

(3)

where G is the equivalent admittance of R, L, C, or the inner resistance R_s of the voltage source respectively,

$$G = \begin{cases} 1/R & \cdots\cdots R \text{ branch} \\ 1/R_s & \cdots\cdots V \text{ branch} \\ 2C/\Delta t & \cdots\cdots C \text{ branch} \\ \Delta t/2L & \cdots\cdots L \text{ branch} \end{cases}$$

(4)

and $I_{km}(t-\Delta t)=$

$$\begin{cases} 0 & \cdots\cdots R \text{ branch} \\ G\cdot u(t) & \cdots\cdots V \text{ branch} \\ -i_{km}(t-\Delta t) - G\cdot[u_k(t-\Delta t) - u_m(t-\Delta t)] & \cdots\cdots C \text{ branch} \\ i_{km}(t-\Delta t) + 2G\cdot[u_k(t-\Delta t) - u_m(t-\Delta t)] & \cdots\cdots L \text{ branch} \end{cases}$$

(5)

Substitute (5) by (3) and then the recursion formula of I_{km} of the inductance and capacitance branch can be written as

$$I_{km}(t-\Delta t) = \begin{cases} -I_{km}(t-2\Delta t) - 2G\cdot[u_k(t-\Delta t) - u_m(t-\Delta t)] \cdots\cdots C \text{ branch} \\ I_{km}(t-2\Delta t) + 2G\cdot[u_k(t-\Delta t) - u_m(t-\Delta t)] \cdots\cdots L \text{ branch} \end{cases}$$

(6)

Considering all independent branches in a network, as shown in Fig.2(b), the node voltage equation is obtained as

$$\boldsymbol{YU} = \boldsymbol{I}$$

(7)

where, $\boldsymbol{Y}$ represents node admittance matrix; $\boldsymbol{U}$ represents node voltage vector, which is to be determined; $\boldsymbol{I}$ represents vector of equivalent current source to each node.

Considering the mutual inductance between each two branches by the method of adding branch circuits[7], the node voltage equation can be written as (7) to solve the voltage of each node.

3. ANALYSIS OF NETWORK SENSITIVITY

A. Simplified Equivalent Circuit

The equivalent circuit model of an 110kV/20MVA Y0/Y power transformer with SF_6 gas insulation is set up as an example. Considering the commonly encountered grounding fault, one resistance is bridged over the node of one unit for double discs and the ground, as shown in Fig.3. (a). Different resistances, namely R_f in Fig.3. (a) and $Z_s(jw)$ in Fig.3. (b), represent different discharge intensities. For the convenience of qualitative analysis and comparison of network sensitivity, the equivalent circuit as shown in Fig.1 could be simplified. Without consideration of voltage regulation windings in B phase and both the A phase and C phase of the power transformer, the inter-phase mutual inductances and inter-phase capacitances can be neglected. The complicated equivalent circuit could be simplified into the model as shown in Fig.3. (b) disregarding the mutual inductances between different discs. The black blocks represent the

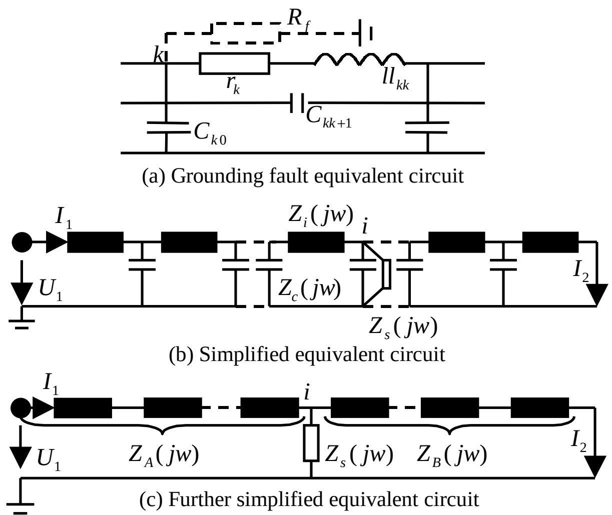


Fig.3. Simplified Circuit

unit for double discs as shown in Fig.3. (a). The whole windings ground through grounding capacitances, namely $Z_c(jw)$ in Fig.3. (b), and the neutral grounding resistance.

For in the considered frequency domain the capacitive impedances of grounding capacitances $Z_c(jw)$ are always much greater than disc-to-ground resistance $Z_s(jw)$ in most cases, the grounding capacitances could be abbreviated furthermore, and thus a further simplified model could be obtained as shown in Fig.3. (c). Though the contributions of many minor factors are overlooked in the further simplified model, the qualitative analysis of network sensitivity may not be affected obviously.

B. Comparison of Network Sensitivity

In this paper, two kinds of network functions will be primarily concerned: driving-point admittance, namely DA, and transfer admittance, namely TA.

Define DA as $H_1(jw) \overset{\Delta}{=} \frac{I_1(jw)}{U_1(jw)}$ (8) where $I_1(jw)$ and $U_1(jw)$ are the frequency characteristics of input current and input voltage signal respectively.

Define TA as $H_2(jw) \overset{\Delta}{=} \frac{I_2(jw)}{U_1(jw)}$ (9) where $I_2(jw)$ is the frequency characteristic of neutral current.

Based on Fig.3. (c), (8) can be expressed as

$$H_1(jw) = \frac{Z_B(jw) + Z_s(jw)}{Z_A(jw)Z_B(jw) + Z_A(jw)Z_s(jw) + Z_B(jw)Z_s(jw)}$$

(10) and (9) can be expressed as

$$H_2(jw) = \frac{Z_s(jw)}{Z_A(jw)Z_B(jw) + Z_A(jw)Z_s(jw) + Z_B(jw)Z_s(jw)} \quad (11)$$

To investigate the effect on network functions caused by grounding fault, the normalized sensitivity of both network functions would be derived and compared.

Normalized sensitivity of $H_1(jw)$ is

$$S_{Z_s}^{H_1} = \frac{\partial H_1 / H_1}{\partial Z_s / Z_s} = \frac{-Z_B^2 Z_s}{(Z_B + Z_s)(Z_A Z_B + Z_A Z_s + Z_B Z_s)} \quad (12)$$

Normalized sensitivity of $H_2(jw)$ is

$$S_{Z_s}^{H_2} = \frac{\partial H_2 / H_2}{\partial Z_s / Z_s} = \frac{Z_A Z_B}{Z_A Z_B + Z_A Z_s + Z_B Z_s} \quad (13)$$

$$\left|S_{Z_s}^{H_2}\right| - \left|S_{Z_s}^{H_1}\right| = \frac{|Z_A Z_B||Z_B + Z_s| - |Z_B^2 Z_s|}{|Z_B + Z_s||Z_A Z_B + Z_A Z_s + Z_B Z_s|} = \frac{|Z_B|(|Z_A||Z_B + Z_s| - |Z_B Z_s|)}{|Z_B + Z_s||Z_A Z_B + Z_A Z_s + Z_B Z_s|} \quad (14)$$

It could be concluded from (14) that when compare the network sensitivity of these two kinds of network functions, which are DA and TA, one of the primary influencing factors is the intensity of grounding insulation fault. When the location of insulation fault is close to the HV terminal, driving-point admittance may have higher sensitivity than transfer admittance under slight grounding discharge, and on the contrary, transfer admittance may have higher sensitivity than driving-point admittance under severe grounding fault.

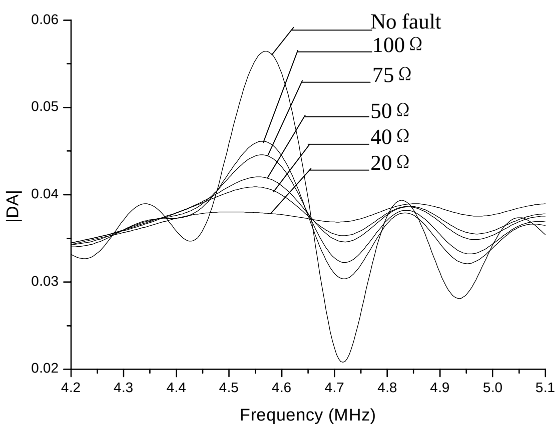
4. SIMULATION AND DISCUSSION

A. Simulation

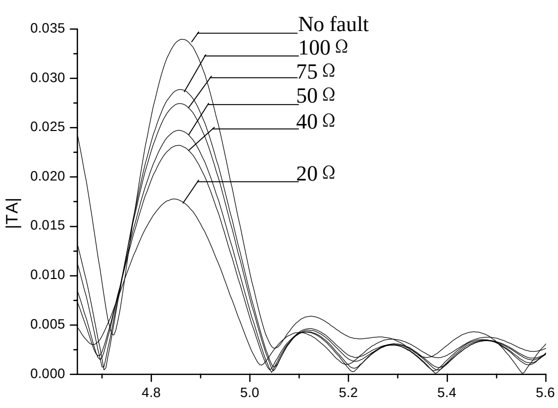
Due to the interleaved winding, the unit formation of equivalent circuit calculated adopts one unit for double discs as shown in Fig.1, where the unit serial number k of

HV winding of each phase is 1,2,…,38 from input terminal to ground terminal and R_s(0.005Ω)is the inner resistance of the input voltage source and R_g(0.005Ω)is the neutral grounding resistance. For the low resistance of the LV section in a step-up or step-down power transformer, the LV winding can be approximated to three-phrase short circuit. While an on line voltage signal is input only in phase B, phase A and C can be considered to be open in transient calculations since the electric network serves as a current source in the transient state. Based on the above supposition and the equivalent circuit as drawn in Fig.1, the input current i_1 and neutral current i_2 can be worked out using Bergeron Method.

Without the loss of generality, in the calculation model, the insulation fault is simulated by connecting a shunt impedance between node *k* and ground as shown in Fig.3. (a). Different shunt impedances, which are labeled as legend in Fig.4, represent different insulation fault intensities. Fig.4 shows the amplitude plot of the driving-point admittance and transfer admittance obtained by using Bergeron method as a result of different grounding fault intensities on the same location, which is disc #18.



(a) DA plot for grounding fault



(b) TA plot for grounding fault

Fig.4. DA and TA of different fault intensities in disc #18

In the analysis and diagnosis of insulation faults in power transformer, frequency shift and pole-height attenuation are of great practical importance. From Fig.4, it could be observed that the pole heights decrease, for both driving-point admittance network function and transfer admittance network function, and yet the pole frequency yields tiny changes. To investigate the pole-height variations, which are clearly noticeable, define

$$\Delta P_1 = \frac{P_1 - P_{1f}}{P_1} \quad (15)$$

as the pole-height change in Fig.4. (a) which is caused by grounding insulation fault. P_1 represents the amplitude of the main pole at around 4.57MHz under normal conditions, and P_{1f} represents the amplitude of the same pole when insulation fault occurs. Similarly, define

$$\Delta P_2 = \frac{P_2 - P_{2f}}{P_2} \quad (16)$$

as the pole-height change in Fig.4. (b). P_2 represents the amplitude of the high frequency pole at around 4.86MHz under normal conditions, and P_{2f} represents the amplitude of the same pole when insulation fault occurs. Here ΔP_1 and ΔP_2 reflect the degree of variation of network functions due to changes of the parameters in the equivalent circuit, therefore the relative magnitude of them represents the relative sensitivity of driving-point admittance and transfer admittance.

A series of ΔP_1 and ΔP_2 are simulated and calculated with different grounding insulation fault intensities in disc #18, and the results are shown in Table 1, in which the data verify the conclusion drawn above. While disc #18 is close to the HV terminal, driving-point admittance has higher sensitivities than transfer admittance under slight grounding fault which is simulated by connecting a relatively large shunt impedance between the corresponding node and the ground. On the contrary, transfer admittance has higher sensitivities with relatively severe grounding fault, which is simulated by adding a

Shunt impedance(ohm)	ΔP_1(%)	ΔP_2(%)
1000	2.69	1.74
100	18.27	14.9
90	18.98	16.33
80	19.97	18.16
75	21.03	19.2
68	21.85	20.81
59	23.78	23.51
58	23.94	23.60
57	23.76	24.07
56	24.43	24.57
50	25.48	27.2
40	27.53	31.70
30	30.35	38.52
20	32.62	47.7
1	38.64	69.5
0.5	37.99	69.78
0.05	35.26	71.69

Table 1. ΔP_1 and ΔP_2 of different fault intensities in disc #18

shunt impedance smaller than about 58 Ω into the calculation model.

Another series of ΔP_1 and ΔP_2 with different fault intensities in disc #15 are also calculated, and the results are shown in Table 2, which are also corresponding to the conclusion.

Shunt impedance(ohm)	ΔP_1(%)	ΔP_2(%)
1000	2.21	1.41
100	15.91	13.4
90	16.64	14.83
80	18.28	16.30
70	19.81	18.33
60	21.62	20.84
50	23.64	23.93
40	25.07	28.52
30	27.92	35.6
20	31.38	44.97
1	32.25	75.13

Table 2. ΔP_1 and ΔP_2 of different fault intensities in disc #15

B. Discussion

The conclusion stated before has a premise that the grounding insulation fault must be close to the HV terminal. If the location of insulation fault is close to the neutral point of the transformer, the conclusion may not apply. However, the location of grounding insulation fault does affect the relative sensitivity of both driving-point admittance and transfer admittance, therefore the regularity of how the fault location affects the relative sensitivity of these two kinds of network functions and how to combine the effects of both the intensity and location of grounding insulation fault need further analysis and discussion.

5. CONCLUSIONS

In this paper, the equivalent circuit of a three-phase power transformer is proposed, based on which a transient calculation model has been brought forward for simulation using Bergeron method. The network sensitivities of two kinds of network functions are derived and compared, which are important in evaluating and diagnosing the insulation condition of power transformer. The simulation results show the potential contribution to evaluate and diagnose the insulation condition through the variation of network function characteristics in the frequency domain more efficiently and accurately by choosing appropriate network function.

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