The extraction of exciting current components opens the door for a further enhancement of electromagnetic circuits' diagnostics

Single-phase exciting current components extraction

Enhancing diagnostic power of exciting current and loss test on power transformers

ABSTRACT

Introduced in 2017, the extraction of exciting current components opens the door for a further enhancement of electromagnetic circuits' diagnostics. Traditionally, analysis of single-phase exciting current and loss data relies on total current, loss and power factor. For some transformers, the prominence of the capacitive current component masks the behaviour of the inductive component, yielding to uncertainties of the diagnostic criteria. The method allows the separation of the essential constituents of the total measured current and the report of all three, namely, I_R, I_L and I_C components. This article describes the method and its diagnostic advantages.

KEYWORDS:

current components, electromagnetic circuit, exciting current, transformer diagnostics

1. Introduction

When first proposed in 1967, analysis of exciting current test results employed only the total current [1]. Advances in test equipment, allowed the measurement of exciting current as a phasor and the test became known as exciting current and loss. Current diagnostic criteria are based on the evaluation of a two-dimensional matrix of currents and watts and the identification of DETC, LTC and phase patterns, which are defined by various phenomena, other than failure modes, influencing the data. The physics behind the data was reviewed in [2].

An equivalent circuit of a transformer under no-load conditions is shown in Fig. 1. The circuit accounts for the energy loss and storage processes when power travels from one winding to another. The leakage impedance, due to magnetically coupled loops (e.g., series units, preventive autotransformers), is not included in the circuit. Losses in the core, mostly due to hysteresis and eddy currents, are accounted for by $\mathbf{R_m}$. The electrical energy stored in the turn-to-turn capacitances as well as in the capacitances to other windings and between windings and ground (all acting as loads) are accounted for by C. The magnetic energy stored in the core is accounted for by $\mathbf{L_m}$.

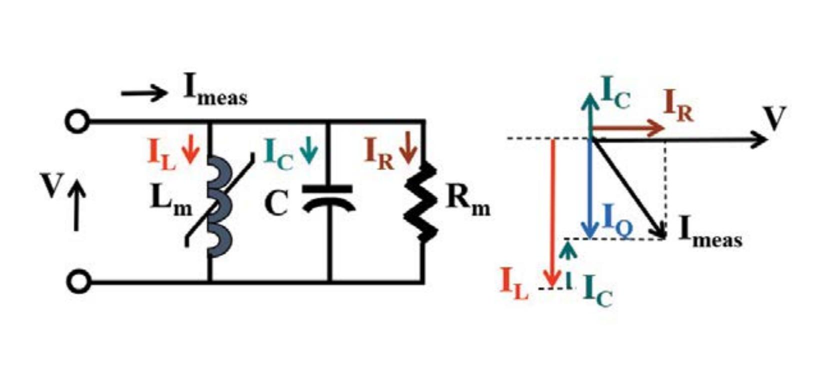

Figure 1. Equivalent circuit of a transformer under no-load conditions

The method that extracts I_L and I_C allows the assessment of electromagnetic circuits free from the effects of capacitive loading

The total measured current ($\mathbf{I}_{meas}$) is comprised of three current components, identified in Fig. 1 as $\mathbf{I}_R$, $\mathbf{I}_L$ and $\mathbf{I}_C$. In most units with lagging $\mathbf{I}_{meas}$, the patterns can be predicted by knowing the core type and inspecting the electrical diagram on the nameplate. In some cases, however, the presence of capacitive loading distorts the expected current patterns, making the diagnostic conclusions less certain. The method that extracts $\mathbf{I}_L$ and $\mathbf{I}_C$, introduced in [4, 5], allows the assessment of electromagnetic circuits free from the effects of capacitive loading.

2. Origin of current components

Understanding the phenomena that dictate the behaviour of the current components is essential for data analysis. A detailed discussion can be found in [2, 3], and a brief synopsis is given below.

2.1. Inductive current – I_L

The inductive current is a function of total inductive loading present during the single-phase exciting current and loss test. The objectives of I_L are twofold: 1) to maintain the core magnetized; hence, it is influenced by changes in reluctance encountered by the flux in the core; and 2) to supply internal inductive loading. The latter is created by bridging positions in inductive type LTCs, series coils for limiting current in bridging positions or circuits with series units. This load may vary with LTC movements.

2.2. Resistive current – I_R

The purpose of $\mathbf{I}_R$ is to supply losses dissipated in the transformer during the test. While these losses are mainly driven by hysteresis and eddy current losses in magnetized cores, the losses in conductors (I^2R) and dielectric losses are also included. For the most part, the pattern of $\mathbf{I}_R$, qualitatively, follows $\mathbf{I}_L$. $\mathbf{I}_R$ is also unaffected by $\mathbf{I}_C$. Therefore, when the interpretation of $\mathbf{I}_{meas}$ is challenged by pattern distortions due to the relative magnitudes of $\mathbf{I}_L$ and $\mathbf{I}_C$, $\mathbf{I}_R$ can serve as a useful diagnostic indicator.

2.3. Capacitive current – I_C

The objective of $\mathbf{I}_C$ is to supply the internal capacitive load. In Fig. 2, $\mathbf{I}_C$ represents the measured capacitive component. As was shown in [2-4], $\mathbf{I}_C$ consists of two currents:

1. Current accounting for the total inductively-coupled capacitive load (red arrows), which includes currents cir-

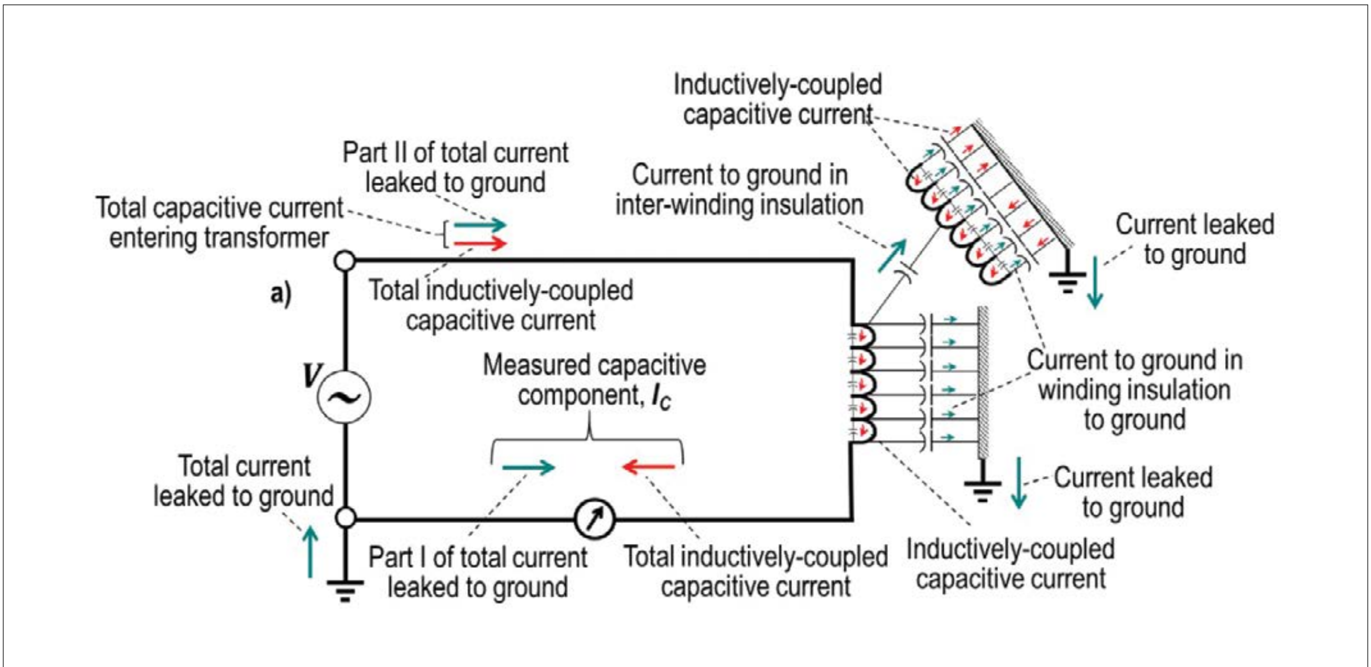

Figure 2. Formation of I_C

Show Current and Loss Referenced to 10 kV							Results														
Setup							Phase A: H1 ⇨ H3, Energize HV1 Measure M3					Phase B: H2 ⇨ H1, Energize HV2 Measure HV1					Phase C: H3 ⇨ H2, Energize HV2 Measure M3				
#	Include in plot/report	Label	DETC (HV)	Label	OLTC (LV)	Test kV	I_L [mA]	I_R [mA]	I_C [mA]	PF [%]	θ [deg]	I_L [mA]	I_R [mA]	I_C [mA]	PF [%]	θ [deg]	I_L [mA]	I_R [mA]	I_C [mA]	PF [%]	θ [deg]
1	☑	DETC-1	5 (Min V)	OLTC-1	1L	10.000	8.778	5.943	-1.006	51.889	-58.742	6.845	2.987	0.117	40.601	-66.045	8.874	6.138	-1.084	52.447	-58.367
2	☑	DETC-1	5 (Min V)	OLTC-1	N	10.000	3.602	5.560	-0.973	77.139	-39.521	1.752	2.700	0.121	85.571	-31.161	3.749	5.777	-1.065	76.726	-39.892
3	☑	DETC-1	5 (Min V)	OLTC-1	1R	10.000	9.288	5.825	-0.997	49.259	-60.489	7.348	2.904	0.124	37.323	-68.085	9.386	6.051	-1.071	50.067	-59.956

Figure 3. Exciting current components extraction featured by Doble Test Assistant

Table 1. Abnormal phase pattern for both I_{meas} and loss. Exciting current components extraction. Case study I

Config.		MVA	kV_{rated}	State	I_{meas}			Loss			I_Q			PF			I_L			I_R			I_C		
Δ-Y	N	20	46-12.47GrdY series xmfr on LV	with defect	36.3	36.9	35.5	259	345	258	25.4	13.0	24.3	L 71	L 94	L 73	18.0	8.2	17.1	25.9	34.5	25.8	-7.4	-4.8	-7.2
				after repairs	37.6	16.9	36.8	271	120	271	26.1	11.9	24.9	L 72	L 71	L 74	20.0	9.1	19.0	27.1	12.0	27.1	-6.0	-2.8	-5.9

culating through insulation-to-ground and currents through turn-to-turn insulation.

2. The total current leaking to ground (green arrows), upon returning to the instrument's ground point, splits into two components. The first one returns to the winding through the measuring circuit (part I) and, therefore, becomes part of the measured current. The second, by returning to the instrument's source (part II), becomes part of the total capacitive current entering the transformer [6].

As a result, two opposing capacitive currents flow through the measuring circuit (Fig. 2). Their values depend on the transformer geometry and the turns ratio. And the direction of the capacitive component reported by the instrument depends on the relative values of these two currents. If the current arriving from the ground is larger than the current that accounts for inductively coupled capacitive load, the measured capacitive component is negative and vice versa.

3. Exciting current components extraction featured by Doble Test Assistant

Historically, the empirical data reported by Doble Test Assistant™ (DTA) included the total current, loss and an indication of whether the current is lagging or leading. The new generation of DTA allows automatic extraction of total current components through an embedded algorithm with additional data now including inductive, resistive, and capacitive currents, as well as power factor and phase angle (Fig. 3). With that, the diagnostic power of the test is improved, as the data can now be evaluated without the impact of capacitive loading.

The new generation of DTA software allows the automatic extraction of total current components

For instance, the analysis of $\mathbf{I_L}$ and $\mathbf{I_R}$ should follow the guidelines outlined for lagging $\mathbf{I_{meas}}$ in [2]. That is, the expected phase pattern on three- and five-legged core-type and shell-type units is of two similar high readings and a lower reading (2H1L), with the latter obtained on the phase located on the middle leg of the core. Other core types and winding configurations might lead to different patterns.

4. Case studies [6]

4.1. Missing turn in one of the parallel strands

The factory test showed an abnormal phase pattern for both I_{meas} and loss (Table 1). Specifically, the middle phase exceeded the outer phases in the N position. A review of current components reveals that distortion comes from I_R while I_L retains the expected 2H1L pattern. Results of the turns ratio test, while all being within 0.5 % of the NP voltage ratio, showed a somewhat different ratio for the middle phase (Table 2). The unit was further tested using the single-phase excitation applied to the LV side at levels up to 110 % V_{rated}. The loss, measured while exciting the middle phase, was the highest throughout the applied voltage range.

The unit was untanked. Inspection of the HV disk-type 3-strand coils revealed the following: one strand in the middle phase was missing a turn in the bottom disk.

The winding was repaired, and the unit retested. Comparing the pre- with post-repair data reveals that I_L and I_C patterns have remained unaffected by the missing turn (Table 1). Such behavior in I_C is rather

Table 2. Results of turns ratio test. Case study I

HV	LV	$Ratio_{NP}$	$Ratio_{meas}$	Δ	I
46000	12470	6.3893	6.3980	0.14	3.0
			6.3950	0.09	3.0
			6.3980	0.14	3.0

Table 3. Abnormal phase pattern for both Imeas and I_{oss}. Exciting current components extraction. Case study II

Config.		MVA	kV_{rated}	State	kV_{test}	I_{meas}			Loss			I_Q			PF			I_L			I_R			I_C		
Y-Y-Δ	N	40	135GrdY/35.5GrdY/13.2 kV	before dielectrics	5	24.2	17.6	25.1	92	67	91	15.7	11.3	17.2	L 76	L 76	L 73	Not reported								
				after dielectrics	10	44.0	53.6	44.0	380	522	379	22.2	12.3	22.3	L 86	L 97	L 86	25.4	18.4	25.0	38.0	52.2	37.9	3.3	6.1	2.7
				after repairs	5	19.9	14.1	19.8	79	58	79	12.0	8.0	12.0	L 80	L 82	L 80	14.4	10.9	14.2	15.9	11.7	15.8	2.9	3.3	2.9

It is expected that further investigation will provide a better understanding of how the location and nature of the fault impact each current component

expected – the missing turn could not produce any tangible change in capacitive loading. The missing turn in one of the parallel strands creates a resistive load that affects I_R but leaves I_L intact. After repairs, I_R shows the expected 2H1L pattern. This example emphasizes the importance of having access to both I_L and I_R components.

4.2 Shorted turns

At the factory, the single-phase exciting current and loss test performed before the dielectric tests showed a normal phase pattern for both I_{meas} and loss. After the dielectric tests (which all passed), the no-load test showed a high loss. The problem was further narrowed down by the single-phase exciting current and loss test. In that, the middle phase exceeded the outer phases in the N position (Table 3). A review of current components has revealed that distortion comes from I_R, while I_L retains the expected 2H1L pattern. The unit was further tested using the single-phase excitation applied to the LV side at levels up to 110 % V_{rated}.

The unit was untanked. Inspection has revealed an electrical failure in the upper half of the center entry HV disk-type 3-strand coil, and it appears that the defect was evolving during the dielectric tests, eventually manifesting itself during the subsequent no-load test.

The winding was repaired, and the unit retested. Comparing the after dielectrics data with after repair data reveals that I_L pattern was not affected by the defect (note the difference in test voltage); I_R, however, after repairs, exhibited the expected 2H1L pattern (Table 3).

5. Conclusions

- The use of extracted exciting current components enhances our ability to evaluate the condition of electromagnetic system without the influence of capacitive loading.
- Having access to type of the core and the nameplate winding electrical diagram allows to define the expected phase, DETC and LTC patterns. These are used as diagnostic criteria in empirical data analysis.
- Presented case studies show a distorted I_R pattern with no influence on I_L pattern, indicating that, in these units, the fault presents only a resistive load for the instrument.
- Further investigation is expected to allow for a better understanding of the impact the location and the nature of the fault have on each of the current components.

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