An online short-circuit impedance estimation approach to power transformer fault detection

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***Abstract*—In addition to offline testing in transformers, advanced diagnostic techniques are experiencing significant advancements in on-line monitoring to ensure the continuity of electrical service and to minimize the costs associated with equipment repair and replacement. This paper presents a strategy for incipient fault detection in power transformers through online measurement of winding impedances. The strategy is based on calculating the series impedance for each phase, which includes the transformer and the connected equipment, by measuring the electrical variables of the transformer. Finally, a single fault indicator is obtained that provides information on the fault severity and the phase affected. The strategy is tested by finite element method simulations for different load conditions and fault severities. The strategy is validated with laboratory results on a 10 kVA three-phase transformer. The results obtained show the effectiveness of the proposed strategy in detecting faults in power transformers.**

***Index Terms*—fault detection, impedance measurement, power transformer, winding impedance**

I. Introduction

Power transformers (PT) are fundamental components in transmission and distribution of electrical energy. The safe and reliable operation of PT is essential to ensure the continuity of electrical service and to avoid the costs associated with the replacement and repair of the equipement in the event of a sudden fault. Approximately an 11% of all electrical faults in power systems are due to PT faults [1]. For this reason, to minimize electric system downtime, early detection of diverse possible faults in PT must be done. In the literature, several techniques can be found and their applicability to the different faults that can occur in PT [2]–[4].

When analyzing the fault spectrum on PT, it can be observed that a significant part of it directly affects the series impedance of the transformer. These faults include loose leads, defective weldings, contact problems at bushings or on-load tap changers (OLTC) such as cocking, pitting and spring malfunctions that affect contact pressure. These type of faults introduce additional contact resistance to the system, producing hotspots or electric arcs that can escalate to a catastrophic fault. As can be seen in Fig. 1, statistically about a 40% of the total faults in PT occur in the windings, about a 27% occur on the OLTC and 7% in the leads [2], [5]. Possible causes of faults in winding connections between windings, tap leads and to bushings are open circuits, short circuits, poor contacts, breaking or loosening. These causes would potentially add series resistance to the system. For this reason early detection and diagnosis of these events would have a major impact on ensuring the reliability of the electrical system.

Currently, there are several offline and online techniques for diagnosing these faults, including static and dynamic resistance measurement, dissolved gas analysis (DGA), vibration measurement, OLTC motor current and power signature analysis, and thermography [6], [7]. Winding resistance measurement, which is an offline test, requires the transformer to be de-energized. This can be challenging in terms of scheduling and downtime, especially for critical power systems where continuous operation is crucial. For the remaining

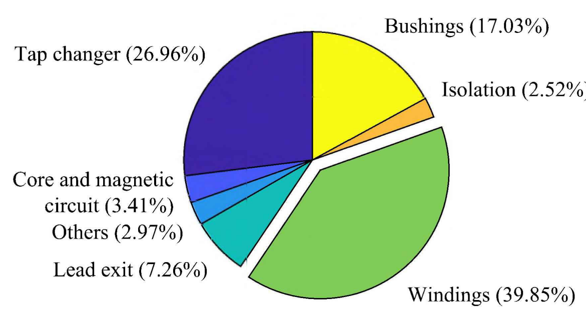

Fig. 1: Fault location analysis based on 675 major faults for $U \geq 100$ kV (adapted from [1])

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techniques, although the transformer can be in operation, additional equipment is required for their implementation, increasing investment and operation costs.

In the literature, there are precedents related to fault diagnosis using electrical variables. One of them is the construction of $\triangle V - I$ locus diagrams [8]–[10]. However, this method is primarily graphical and relies on observing the locus diagram and comparing it with previous states. This technique is mainly used to detect winding deformation and has not been attempted to diagnose contact faults.

A proposal for online monitoring of transformer ratio, short-circuit impedance and power losses has been presented in [11]. For this, a regression-based method is used to estimate the variables to be monitored. Specifically, changes in winding impedance reflect contact problems and geometrical distortion of the windings. However, the study does not analyze concrete cases that show the detection and diagnosis of such faults, but only shows the behavior of online monitoring of power transformers. To obtain the short-circuit impedance, the voltages and currents on both sides of the transformer are measured, and the effect of the excitation current is considered. Consequently, the proposal depends on the quality of the signals provided by the ordinary instrument transformers. So, there is a certain risk of misinterpreting a fault or other abnormal behavior of an instrument transformer as a transformer fault. In [12], two case studies are presented where it is possible to detect instrument transformer problems and core saturation due to suspected DC bias.

In [13], the importance of moving from offline to online diagnostic methods is highlighted. The work focuses on transformer winding deformation diagnosis through advanced methods based on signals analysis. These include vibration measurement, communication method, high-frequency signal injection, ultrasound reflection, short-circuit impedance measurement and transfer function measurement in time domain (*Low Voltage Impulse* -LVI-) or frequency domain (*Frequency Response Analysis* -FRA-). Based on a case study presented, the capability of FRA compared to short circuit impedance for transformer winding deformation diagnosis has been clarified. However, further studies were recommended to address the theoretical and practical challenges studied for replacing offline methods by online applications. In this sense, online short-circuit impedance measurement has been introduced as an advanced and economical method in transformer winding deformation diagnosis where some researchers have arguably discussed the accuracy of this method.

In [14], a method for the online extraction of winding parameters of a single-phase transformer is presented. From simulation cases, the proposed technique is found to be sufficiently accurate to monitor minute changes in the equivalent parameter values regardless the input signals and loading conditions.

In [15], a method based on differential equation algorithm (DEA) is used to obtain the equivalent circuit parameters of a single-phase transformer. The advantage of this proposal is that three consecutive voltage and current samples are sufficient to compute the estimated parameters. In [16], an alternative method for determining the winding resistance from the power measurement is proposed. However, the method is currently only applicable to the no-load condition.

A parameter identification method using the least squares method based on orthogonal decomposition to identify the leakage inductances and resistances of transformer windings is proposed in [17]. Although the algorithm provides a good basis for transformer parameter identification and has potential for practical application, no field cases are presented.

As can be seen, there are investigations to obtain transformer parameters online. However, they have not been related to concrete cases of detection of winding resistance increase, but rather to mechanical deformations. Also, several proposals are applicable to single-phase transformers and their extrapolation to three-phase transformers has not been carried out. This paper presents a technique based on the online measurement of electrical variables of the transformer, to detect incipient faults using a simple indicator obtained by estimating the series impedance. The aim of this technique is to adapt the offline static and dynamic resistance measurement to an online approach, eliminating the need of additional equipment to that already installed in substations and used by conventional protection devices. In this way, variations in series impedance can be detected from the current and voltage measurements available in the transformer, without the need to take it out of service.

II. Description of the Proposal

The aim of the proposed strategy is to determine the presence of faults associated to contact resistance by estimating the series impedance, that includes the transformer and connected devices. Fig. 2 shows the connection scheme. Here the measurement system can be observed, that includes the transformer and a variable resistor which emulates the fault and defines its severity. Outside the measurement system the power supply and a resistive load can be observed. A preliminary conclusion is that the system provides protection to the elements between the measurement connection, similar to a differential protection [18].

A first strategy was the monitoring of differential voltages $(\dot{V}_1 - \dot{V}_2^{'})$. This would be a simple way of observing series impedances, since this voltages represent the voltage drop on the impedances. As stated, this would be a simple strategy, but lacks immunity in the face of unbalances and load variations conditions.

A second approach would be the monitoring of series impedance directly. For this purpose, currents and voltages (usually available in PT) at both sides are used. With these variables registered, (1) is applied to each phase to obtain the series impedance, where $\dot{Z}_e$ is the estimated impedance. Fig. 3 shows the equivalent circuit of the single-phase transformer with the variables involved in the calculation of the series impedance and its parameters, where R_1 and X_{d1} are the resistance and leakage reactance of the primary winding, respectively, $R_2^{'}$ and $X_{d2}^{'}$ are the resistance and leakage

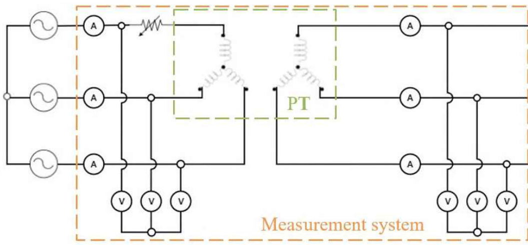

Fig. 2: Measurement scheme model.

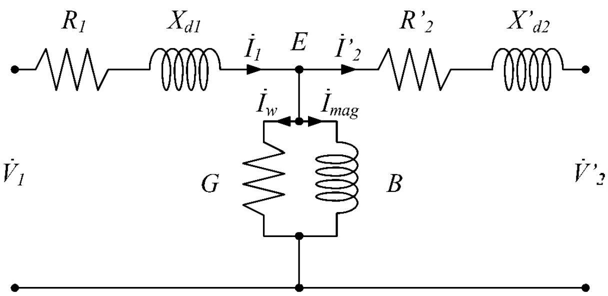

Fig. 3: Simplified equivalent circuit of single-phase transformer.

reactance of the secondary winding with respect to the primary side, respectively, and G and B are the conductance and susceptance of the magnetizing branch, respectively. This strategy is complex compared to the differential voltages, but gains partial immunity to load variations and unbalances. Note that $\dot{Z}_{\mathrm{e}}$ is not directly the series impedance, but is affected by the magnetizing impedance due to the calculation mode. Strictly, the series impedance is defined as in (2). As can be seen, it is different from the estimated one, although in real field applications it is not possible to measure the induced voltage $\dot{E}$. Therefore, it is necessary to deal with this difference.

Working with (1) and (2) the error can be obtained, according to (3), where $\dot{I}_0$ is the no load current.

$$\dot{Z}_{\mathrm{e}} = \frac{(\dot{V}_1 - \dot{V}_2')}{\dot{I}_1} \tag{1}$$

$$\dot{Z} = \frac{(\dot{V}_1 - \dot{E})}{\dot{I}_1} + \frac{(\dot{E} - \dot{V}_2')}{\dot{I}_2'} = \dot{Z}_1 + \dot{Z}_2' \tag{2}$$

$$\triangle\dot{Z} = \dot{Z}_2' * \frac{-\dot{I}_0}{\dot{I}_1} \tag{3}$$

To overcome this error, a phasor sum is proposed, where each estimated impedance is coupled to the corresponding phase by assigning them an angle of 0, $2/3\pi$ and $-2/3\pi$. Equation (4) shows the resulting indicator.

$$\dot{\mu} = \dot{Z}_a + \dot{Z}_b + \dot{Z}_c \tag{4}$$

The use of this indicator offers additional advantages. The first one is the possibility of being independent of the OLTC position. OLTC operation results in addition or subtraction of parts of the winding, that directly affects its resistance [19]. A second advantage is the compensation of the resistance change due to temperature variation. In this scenario the resistances in the three phases would be affected by temperature. Assuming that the system would be at the same temperature, the changes in the resistances values would be equal. The last is that the no-load condition can be useful to determinate the fault location. If a fault is detected at no-load, it must be on the primary side, because it is used in the calculation of (1). On the contrary, if a fault is detected under load but is not visible under no-load condition, i.e. the current is not flowing through the fault, then it must be on the secondary side. This is possible since primary side current is used as a reference and has a value at no-load condition, in this case an impedance proportional to Z_1 is calculated. This is obtained by replacing in (3) the load current by the no-load current and subtracting (3) from (1).

Both the error in the estimation of the series impedance, the OLTC position and the temperature variation cause changes of the same magnitude in the measured impedance of the three phases. This effect is compensated by the sum of the three impedances phased by $2/3\pi$. Furthermore it has been mentioned that in the no-load condition an impedance proportional to $\dot{Z}_1$ is seen. This impedance is equal in the three phases so once again it is compensated by the use of this indicator.

As can be deduced from the mentioned errors, the measured impedance, and thus the indicator, does not represent an accurate measurement of the actual impedance. Nevertheless, it indicates the presence of additional resistances in the system, making it useful for the detection of faults affecting the winding resistance.

A. *Offline winding resistance measurement: case studies*

This subsection presents cases studies where faults were detected by offline winding resistance measurement. Table I shows the results obtained for each case in terms of winding resistance values and the ratio between the maximum value and the reference value. The latter gives an idea of the range of faults encountered in field cases, for which the proposed strategy should be implemented to ensure its representativeness.

Fig. 4 shows the source of the fault for the cases where visual inspection was documented.

TABLE I: Offline winding resistance measurement: case studies

Case	Side	Winding resistance @ 75°C (mΩ)					Resistance ratio [c] (p.u.)
		U-V [a]	*V-W* [a]	*W-U* [a]	*Mean value*	*Ref. value* [b]	
1	HV	269.8	237.6	236.6	248.0	237.1	1.14
2	HV	459.9	386.1	411.9	419.3	350.4	1.31
3	HV	15738	16331	23980	18683	15046	1.59
4	LV	154.4	368.3	154.1	225.6	166.7	2.21
5	HV	663.8	646.1	601.3	637.1	579.7	1.15

[a] With respect to neutral (N) in case of LV side.
[b] Mean value of Factory Acceptance Test (FAT).
[c] Ratio of the highest measured resistance value to the FAT tests [b].

(a) Case 1: high resistance point on the fixed contact of the De energized tap changer (DETC).

(b) Case 2: high resistance point on the moving and fixed contact of the DETC.

(c) Case 4: loose bushing contact inside the tank.

(d) Case 5: high resistance point on the moving contact of the DETC.

Fig. 4: Visual inspection of case studies.

III. Results

To validate the proposed strategy, simulations and experimental tests were performed. For this purpose, additional resistors were added in each phase (one by one) according to Table II. Each case is discussed in the following subsections.

The cases presented in Table II were selected according to the resistances ratio stated in subsection II-A, resulting in the range of fault severities from $0.1\ p.u.$ to $1\ p.u.$

A. Simulations

A first approach to demonstrate the applicability of the proposal is to simulate the transformer using the finite element method (FEM). Fig. 5 shows the model used to apply the FEM. In the model, the structure of the core and the cross-sectional areas of windings are represented. The non-linear characteristic of the core is included. The windings are represented as primary and secondary, defined as copper strands.

The software allows for steady-state calculations. It has the possibility to connect the model to an external electrical circuit. The model takes into account the magnetic structure, allowing for the obtainment of the characteristics of the magnetizing reactance and to estimate the iron losses. In the external circuit, the values of windings resistances and leakage reactances are included, represented by the classical model of a transformer. Fig. 6 shows a per-phase representation of the model.

TABLE II: Simulated and experimental tests conditions

	Additional fault resistance (p.u.)	**Load (p.u.)**	
		0 (no-load)	***0.63***
Fault Severity	0 (healthy)	•	✓
	0.1	•	✓
	0.2	-	✓
	0.4	-	✓
	0.5	•	-
	0.6	-	•
	0.8	-	•
	1	•	✓

• Simulated case only.
✓ Simulated and experimentally validated case.

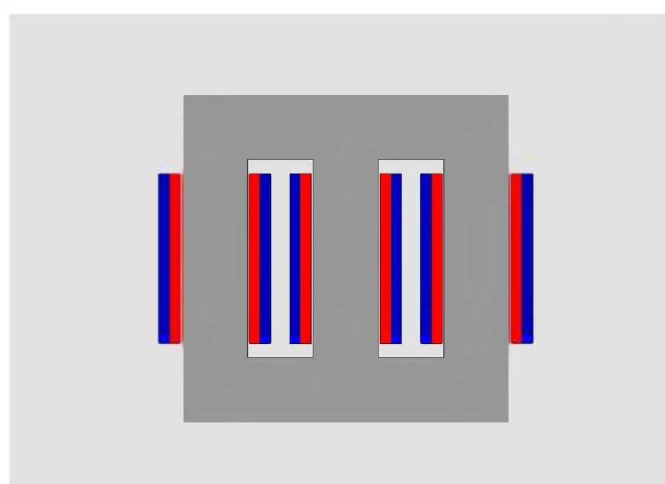

Fig. 5: Transformer scheme for FEM analysis.

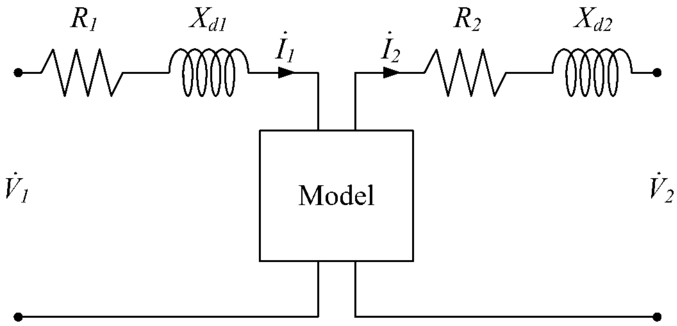

Fig. 6: External circuit used in the FEM model.

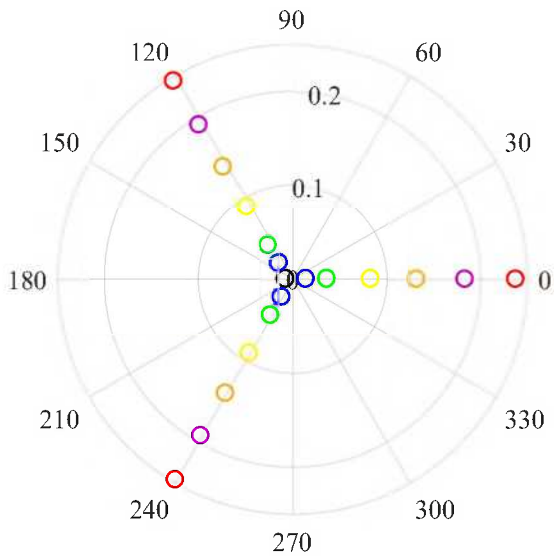

Fig. 7: Simulation Results for a 0.63 p.u. load — Black: healthy, blue: 0.1 p.u, green: 0.2 p.u, yellow: 0.4 p.u, orange: 0.6 p.u, purple: 0.8 p.u, red: 1 p.u.

From the simulation, the variables of interest are extracted (phase voltages and currents) to then apply (1) and (4).

The analyzed states are shown in Table II, where the fault severity is expressed as the ratio between the additional fault resistance and the winding resistance. Fig. 7 shows the results on the polar plot, i.e., the indicator μ. A proportionality is observed between the fault severity and the magnitude of the indicator. It is possible to determine the affected phase by analyzing the angle of the indicator, which is aligned to the faulty phase.

Another case analyzed is the no-load condition, with different faults severities. The aim of this simulation is to verify the hypothesis stated in section II. Fig. 8 shows the indicator on the polar plot. It can be observed how the fault is diagnosed under no-load condition. This indicates that the fault is located on the primary side, which is correct.

B. Experimental implementation

To validate the diagnosis strategy, the proposal was implemented experimentally on a laboratory test bench. The laboratory test bench consist of a three-phase transformer

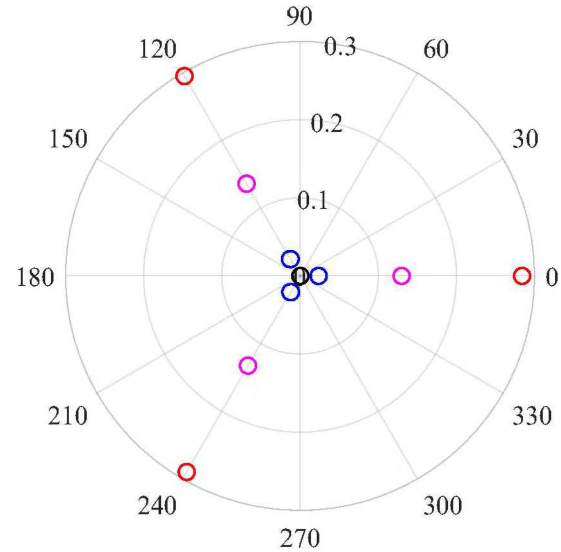

Fig. 8: simulation results for no-load condition — Black: healthy, blue: 0.1 p.u, magenta: 0.5 p.u, red: 1 p.u.

($10kVA$, $8.74A$, $660V$, 260 turns $\pm5\%$ per winding, vector group $Yy0$, transformation ratio 1:1), resistive loads (load factor 0.63, unitary power factor), a measurement system (Voltage dividers, current clamps and a data acquisition board) and three variable resistors to simulate and control the faults. Table II shows the tested cases presented as the fault resistance ratio.

Fig. 9 shows the indicator obtained on the polar axes. It can be seen how the value of the indicator increases with the severity of the fault. It can also be observed which the faulty phase is, by analyzing the angle of the indicator. In this sense, the indicator is aligned to the corresponding phase with a certain phase shift.

IV. Conclusions

A novel approach for fault detection in power transformers through online estimation of short-circuit impedance was presented. Sensitivity to series faults and the capability to detect contact resistance with no additional equipment has been demonstrated. The proposal relies on the use of an indicator obtained by measuring voltages on both sides of the transformer and the primary current that has proven to have the following advantages:

- immunity to load variations,
- immunity to OLTC position,
- capability to indicate fault location due to no-load behavior,
- immunity to resistance change due to thermal effect,
- immunity to voltage and load unbalance.

The presented advantages have been validated through simulations and experimental implementation, except for the no-load condition, which lacks on the experimental. The proposed method has demonstrated capability in the detection of incipient faults, reaching a sensitivity according to the faults presented in the case study.

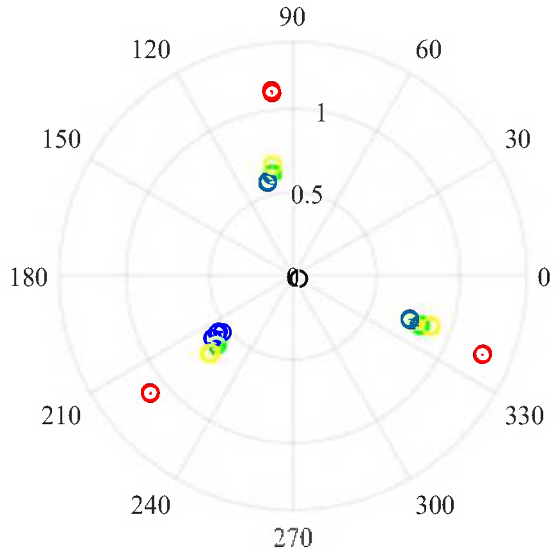

Fig. 9: Experimental Results for a 0.63 p.u. load — Black: healthy, blue: 0.1 p.u, green: 0.2 p.u, yellow: 0.4 p.u, red: 1 p.u.

Additionally, some discrepancies can be observed between simulations and experimental. While the relation between fault severity and the indicator is linear in simulations, in the experimental a different behavior is observed. There can be seen a strong sensitivity for low fault severity, and a minor variation while severity increases.

As future work, the adaptation of the strategy, the capability and difficulties in the diagnosis of PT will be analyzed for different vector groups of transformer. Moreover, the behavior of the proposal will be tested on fault severity lower than 0.1 p.u.

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