International Conference on Renewable Energies and Power Quality (ICREPQ'15)
La Coruña (Spain), 25th to 27th March, 2015
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.13, April 2015

Investigation and Understanding the Conditions of Power Transformer Internal Faults using On-line Technique

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Abstract. Loss of a power transformer in a utility, generation plant or process can cost many millions of pounds, depending on how long it is out-of-service. Internal faults are said to be the most likely cause of disruption in transformer performance and interruption of power supply. Improving understanding of the relationship between types of problem in transformers and their indicators will help to identify internal faults and their locations. Developing an on-line method to monitor and investigate the health conditions of the transformer will help asset managers assess plant while it is operational, leading to reduced running costs and increased life. The proposed method is based on measuring electrical parameters at both sides of a transformer to differentiate between healthy and faulty conditions while it is still in service. In this study, two windings of five sections each have been simulated. The values for each section's resistance and impedance are calculated based on copper windings, interleaved construction and insulation between sections. The simulated power transformer is connected to an inductive load. Comparison of simulated input and output voltages and currents has been conducted to identify indicators of the transformer's health status.

Developed faults at different locations in the transformer windings are used to study the transformer performance and to recognise the fault indicators. The simulation results show very clearly that there are trends in the measured parameters that are attributed to the type of fault within the transformer. Hence a simple logic comparator can be easily deployed to identify the fault location in relation to the transformer health status.

Key words

Transformer health condition, short circuit, current and voltage measurement

1. Introduction

The power transformer is considered to be the heart of the electrical network, due to its importance in transferring power into different levels. A fault in this high cost, critical device can be the main cause for a complete outage of the network [1]. However, to get best value for investment from such devices companies normally try to keep their transformers operating at high efficiency and running for as long as possible. Power transformer reliability is really dependent on how good the insulation system is and how it is able to withstand the different stresses. Inherent stresses in the transformer, including heat produced by high current loading, affect the insulation and provides the opportunity for Partial Discharge (PD) or short circuit faults to occur, therefore insulation degradation results in power outage [2, 3]. The very high current under short circuit conditions leads to high mechanical force on the windings, changing the dimensions through axial or radial deformation [4, 5, 6, 7]

If winding failures occur for any reason and these faults are detected at an early stage then fault effects can be limited and the losses will be less. However if these faults are not identified, then the efficiency and reliability of the device will be reduced and may result in a complete power outage [8, 9]

A fault condition affects voltage and current waveforms. Transfer function (TF) is currently used for off-line power transformer monitoring and fault diagnosis. Research has shown that TF is appropriate for detection of dielectric failures and winding deformation. The transfer function method is an off-line method, which means that the transformer has to be removed from service for transformer condition monitoring [10, 11]. Another off-line method, the Frequency Response Analysis (FRA), can be used for finding mechanical deformation and winding displacement faults in power transformers [12, 13].

In this study, an on-line identification method for internal fault detection is investigated by using the measurement of both voltages and currents in both transformer windings for fixed frequency and connected to constant load. The impedance of the transformer windings has been calculated and used to determine the optimum load that can be connected to the transformer. The impact of a short circuit between winding sections, sections to ground and between two windings has been considered. The effect of the fault location on the measured input and output currents and voltages has been studied in an effort to relate the internal fault to measurable parameters. The transformer model for the simulation is developed by using PSPICE software.

2. Transformer Model and Faults

A modified version of the transformer model set out in [14], for modelling a one to one power transformer containing two interleaved windings each of which has five sections that contain twenty turns, is used in this work. Each of the five sections is represented by lumped resistance, inductance, shunt and series capacitances. The values are determined by the coil construction and the insulation between section to section and section to core. The parameters for the modified model are as shown in Table I. The two windings are linked due to the mutual inductance that is dependent on the transformer construction. As outlined in [14] the model considers air core and two insulation materials, i.e. a thickness of 0.1 mm solid insulation (paper) is around the conductor and the primary and secondary windings are immersed in oil to provide insulation and cooling. The system is simulated under 230 V, 50 Hz supply on the primary winding of the transformer for a defined constant load. In the simulation the primary voltage and current and the secondary voltage and current are monitored.

Table I : Power transformer model parameters

Components	Values
Primary section resistance R_P	1.2 Ω
Secondary section resistance Rs	1.2 Ω
Primary section inductance L_P	7.2H
Secondary section inductance L_S	7.2H
Primary and secondary series capacitance C_{S1}, C_{S2}	0.0133nF
Primary and secondary shunt capacitance C_{g1}, C_{g2}	3nF
Capacitance between windings C_w	5nF

The primary and secondary winding impedances for a healthy transformer are consistent however this is not the case when the transformer suffers from winding deformation or cross-turns short circuit. Therefore, the expected primary/secondary voltages/currents will deviate from the designed values under known load conditions. Short circuit between sections normally occurs if the insulation between the sections has degraded due to electrical or mechanical stresses, resulting in changes in winding impedances. Figure 1 indicates the current flow during short circuit between sections and between windings; accordingly, the winding impedances differ.

If the short circuit occurred between node 2 and 3, this is equivalent to removing one section from the overall model and the mutual inductance will be different accordingly.

In theory shorting one section in the transformer primary winding will have the same impact irrespective of its actual location. Similarly, a short across one section of the secondary will produce similar, but different, measurable changes.

If the short circuit occurred between primary and secondary windings such as between node 3 primary winding to node 4 secondary winding, this leads to current flow providing a direct connection between windings. This affects the mutual inductance and leads to changes in the turns ratio of the transformer according to number of healthy nodes in both sides. Similarly, for short circuit between node 3 secondary winding and node 4 in the primary winding, the number of healthy nodes in both windings will be different leading to changes in the measurable parameters.

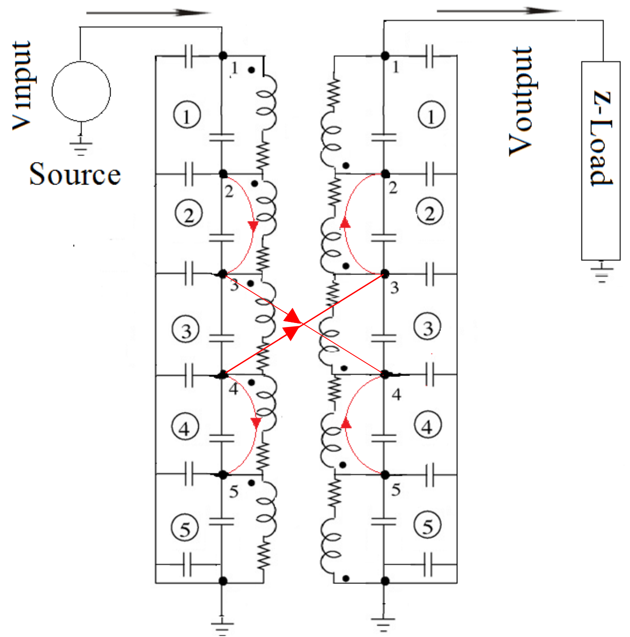

Fig. 1. Short circuit of current flow between sections and windings

3. Healthy Transformer Parameters

The construction of the model and the connection to the load is shown in Figure 2, and Table II shows the load parameters.

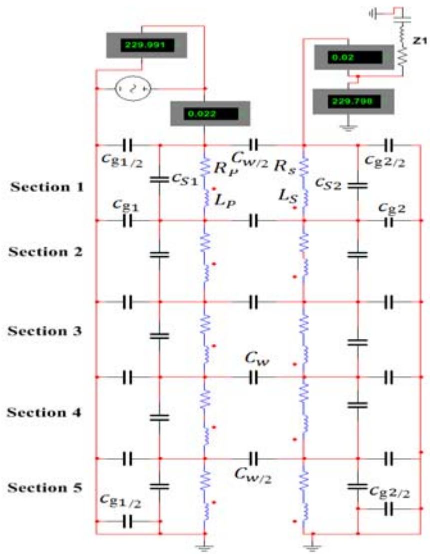

Fig. 2. Two windings transformer load

Table II. Load parameters

Total impedance	11309.7 Ω
Total reactance	6784.3Ω
Resistance	9048.9 Ω
Inductance	27.9 H
Capacitance	1.59μF
Power factor	0.8

The healthy transformer was investigated using PSPICE measuring instruments for voltage and current in both sides of the transformer. The measured voltage and current signals for healthy internal conditions, such as good insulation and no internal faults, will be compared with the values from transformers with simulated internal faults.

4. Short Circuit Test

4.1 Primary Winding Faults

As introduced earlier, the primary winding of the simulated transformer contains five sections. The faults simulated are inter-turn short circuits between different sections. Short circuits between sections depend on the insulation condition. Another type of fault that could occur is the short circuit between any section and the core. Four scenarios of faults are considered in this study, they are; one section shorted, two sections shorted, three sections shorted, four sections shorted and section to core short circuit, this represents all possible 14 short circuit conditions. The faults and locations are shown in Table III. The experimental procedure has been used to understand the measurable parameters for possible primary winding faults due to shorted sections.

Table III **:** Measured parameters for primary winding faults

No	Fault	Vin (Volts)	Iin (Amps)	Vout (Volts)	Iout (Amps)
1	Section 1 to 2	229.99	9.599	229.809	0.02
2	Section 2 to 3	229.99	9.599	229.809	0.02
3	Section 3 to 4	229.99	9.599	229.809	0.02
4	Section 4 to 5	229.99	9.599	229.809	0.02
5	Section 4 to ground	229.99	9.599	229.809	0.02
6	Section 1 to 3	229.99	25.572	229.803	0.02
7	Section 2 to 4	229.99	25.572	229.803	0.02
8	Section 3 to 5	229.99	25.572	229.803	0.02
9	Section 3 to ground	229.99	25.572	229.803	0.02
10	Section 1 to 4	229.99	57.518	229.801	0.02
11	Section 2 to 5	229.99	57.518	229.801	0.02
12	Section 2 to ground	229.99	57.518	229.801	0.02
13	Section 1 to 5	229.99	153.35	229.796	0.02
14	Section 1 to ground	229.99	153.35	229.796	0.02

Study of the measured parameters demonstrates that the values of voltages and currents are not affected by the location of the shorted sections but are affected by the number of shorted sections. The number of shorted sections in the primary winding has different effects on the measured parameters, as shown in Table III. The most obvious change is that the greater number of shorted sections the higher is the input current, as seen in Figure 3. Shorted sections increase the input current from 0.02 A for a healthy transformer up to 9.6 A, 25.62 A for two, 57.5 A for three and 153.4 A for four shorted sections respectively. Output voltage is not much affected, it can be seen that as the number of shorted sections increases the output voltage reduces. However, the small change would be difficult to detect in practical situations and this effect is not considered as an important conditions of this type of fault. The output current is not affected by any of the primary winding faults tested. Therefore, the input current is the main conditions for indicating primary winding faults.

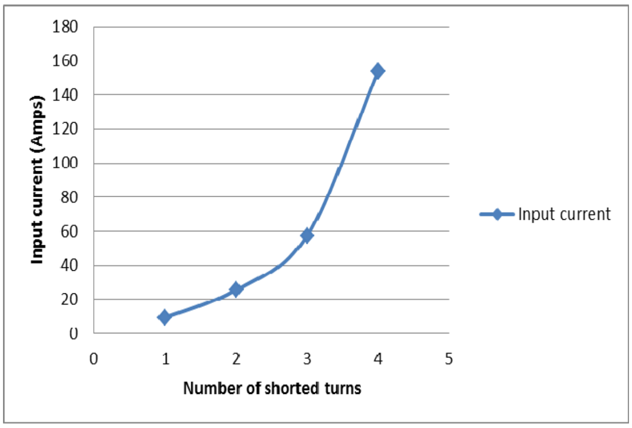

Fig. 3: Impact of shorted primary sections on primary current

4.2 Secondary Winding Faults

The secondary winding contains five sections, the inter-turn short circuits are simulated between sections to sections and between sections to ground. Four scenarios of faults are considered in secondary winding for different number of shorted sections and sections to ground similar to the four scenarios in primary winding to represent all 14 faults that have been studied to investigate their impact on the input and output signals of the transformer. Table IV shows the measured voltage and current for all faults considered in the secondary windings.

The results indicate that the outcomes of the simulations can be grouped in a similar manner to the primary investigation. It is again shown that the fault location has no effect on the measured parameters. As discussed for the primary winding faults, the more shorted section the higher the fault effect for the secondary winding faults.

Table IV: Measured parameters for secondary winding faults

No	Fault	Vin (Volts)	Iin (Amps)	Vout (Volts)	Iout (Amps)
1	Section 1 to 2	229.99	6.396	153.25	0.013
2	Section 2 to 3	229.99	6.396	153.25	0.013
3	Section 3 to 4	229.99	6.396	153.25	0.013
4	Section 4 to 5	229.99	6.396	153.25	0.013
5	Section 4 to ground	229.99	6.396	153.25	0.013
6	Section 1 to 3	229.99	10.955	98.532	0.008
7	Section 2 to 4	229.99	10.955	98.532	0.008
8	Section 3 to 5	229.99	10.955	98.532	0.008
9	Section 3 to ground	229.99	10.955	98.532	0.008
10	Section 1 to 4	229.99	14.376	57.487	0.005
11	Section 2 to 5	229.99	14.376	57.487	0.005
12	Section 2 to ground	229.99	14.376	57.487	0.005
13	Section 1 to 5	229.99	17.038	25.555	0.002
14	Section 1 to ground	229.99	17.038	25.555	0.002

It can be stated that the type of fault influences the measured parameters but the fault location has no effect.

Figures 4, 5 and 6 show that, in the case of short circuit secondary coils, output current, output voltage and input current are affected. Figure 3 demonstrates that as the number of turns short circuited increases the input current also increases. Figures 5 and 6 demonstrate that, in contrast, the output voltage and current decrease.

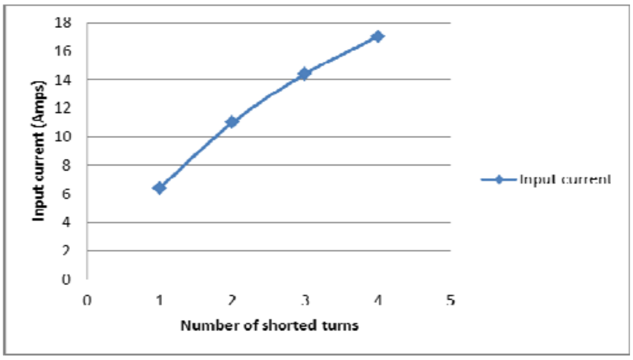

Fig. 4: Impact of shorted secondary sections on primary current

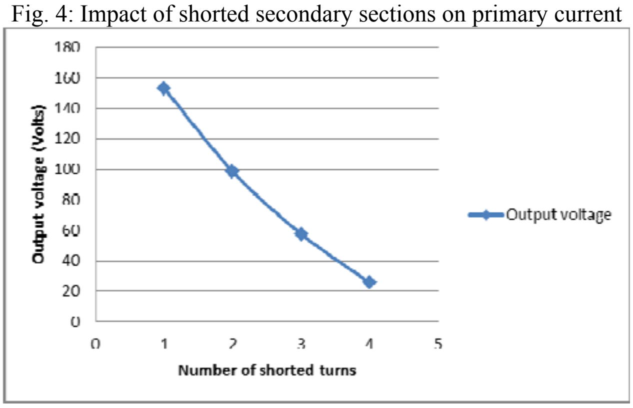

Fig. 5: Impact of shorted secondary sections on secondary voltage

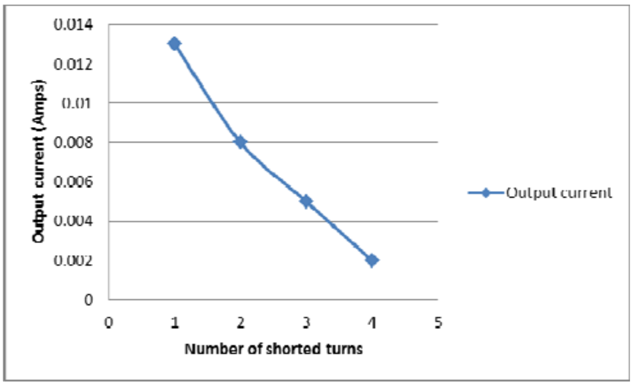

Fig. 6: Impact of shorted secondary sections on secondary current

4.3 Cross windings short circuit

Power transformer windings, although magnetically linked, are not galvanically linked. This galvanic isolation provides protection in systems. A short circuit between primary and secondary windings may occur between different locations. This kind of short circuit is different to the cases discussed previously because current will travel directly between the two windings. This will completely change the application of the transformer. Studying the faults conditions between windings are divided as follows:-

4.3.1 Similar sections short circuit

The faults considered here are short circuit between section 1 primary winding and section 1 in secondary winding, etc. The simulated measurement parameters, shown in Table V, suggest that this type of fault does not affect the measurable input parameters and output current but has minimal effect on the measurable output voltage. The small change in output voltage is graphed in Figure 7. This type of fault would be difficult to identify using the measurable parameters in the simulation.

Table V: Measured parameters for short circuit faults between at similar locations in the windings

No	Fault	Vin (Volts)	Iin (Amps)	Vout (Volts)	Iout (Amps)
1	1 Primary to 1 Secondary	229.99	0.022	229.958	0.02
2	2 Primary to 2 Secondary	229.99	0.022	229.925	0.02
3	3 Primary to 3 Secondary	229.99	0.022	229.879	0.02
4	4 Primary to 4 Secondary	229.99	0.022	229.833	0.02

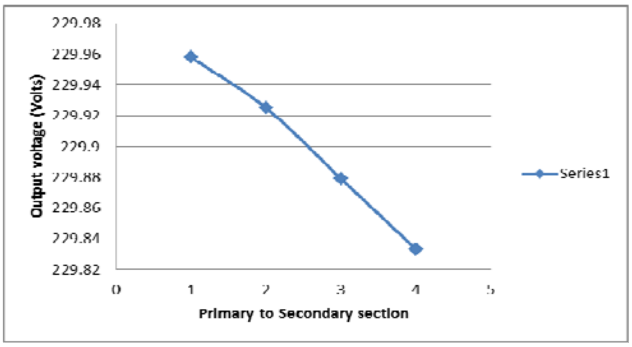

Fig. 7: Secondary voltage for short circuit between similar primary and seconday windins

4.3.2 One section cross-over short circuit

The faults considered here are short circuit between dissimilar sections in primary and secondary windings, i.e. 1 primary winding and section 2 in secondary winding, etc. The simulated measurement parameters, shown in Table VI, suggest that this type of fault does affect the measurable parameters and that the changes in output may be able to be used to identify fault type.

Cross-over faults have short circuit between two un-like section locations, therefore the transformer turn ratio will be affected due to the direct connection between the two affected sections. For the short circuits which form between higher voltage sections in primary coil to lower sections in secondary coil, shown in yellow in Table VII, the input current and output voltage become higher, with a slight increase in output current compared to the healthy state. For the short circuits which form between higher voltage sections in secondary coil to lower sections in primary coil, shown in orange in Table VII, the input current and output voltage are again affected compared to the healthy state.

Table VI: Measurement parameters for short circuit between dissimilar locations in the windings

No	Fault	Vin (Volts)	Iin (Amps)	Vout (Volts)	Iout (Amps)
1	1 P - 2 S	229.99	1.393	279.2	0.024
2	2 P - 3 S	229.99	1.94	275.86	0.024
3	3 P - 4 S	229.99	3.216	268.144	0.024
4	1 S - 2 P	229.99	0.923	186.152	0.016
5	2 S - 3 P	229.99	1.288	183.937	0.016
6	3 S - 4 P	229.99	2.139	178.804	0.016

Figures 7 and 8 show the changes in input current and output voltage respectively, indicating how a short circuit between windings affects the parameters.

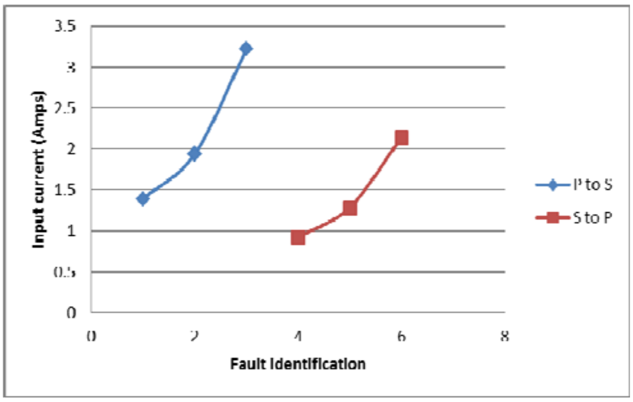

Fig. 7: Primary current for short circuit between dissimilar primary and secondary windings

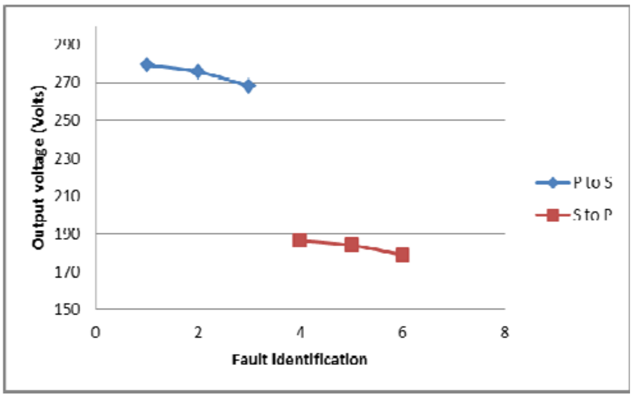

Fig. 8: Secondary voltage for short circuit between dissimilar primary and secondary windings

The impact of this fault on the output current is consistent for a given short circuit link. For a given fault arrangement the current remains constant, as shown in Table VII.

4.3.3 Short Circuit between dissimilar winding sections – 2 sections.

This section reports on the simulations carried out to investigate a short circuit which traversed two turns in the primary-secondary arrangement. Table VII shows the short circuit faults considered in this section and the results of the simulations.

The values in Table VIII indicate that input current and output voltage are the most significant indicators of a fault. The magnitudes of voltage and current are significantly different from those in previous fault conditions and could be helpful in identifying the fault.

Table VII**:** Measurement parameters for short circuit between windings across two sections

No	Fault	Vin (Volts)	Iin (Amps)	Vout (Volts)	Iout (Amps)
1	1 Primary to 3 Secondary	229.99	8.552	322.066	0.029
2	2 Primary to 4 Secondary	229.99	12.806	306.45	0.029
4	1 Secondary to 3 Primary	229.99	3.657	142.351	0.012
5	2 Secondary to 4 Primary	229.99	5.481	131.388	0.012

4.3.4 Short Circuit between dissimilar winding sections – 3 sections

In these simulations the first section in primary winding is shorted to the last section before the bottom of the secondary winding or a similar arrangement from secondary to primary sections.

Table VIII: Measurement parameters for short circuit between windings across over three sections

No	Fault	Vin (Volts)	Iin (Amps)	Vout (Volts)	Iout (Amps)
1	1 Primary to 4 Secondary	229.99	34.541	367.751	0.032
2	4 Primary to 1 Secondary	229.99	8.627	91.979	0.00807

The values in Table IX indicate that input current and output voltage are the most significant indicators of a fault. Comparing these with the previous data, the magnitudes of voltage and current are significantly different and could be helpful in identifying the fault type.

5. Conclusion

In this paper, measure primary/secondary voltage/current is used to simulate the measurable values which would result from a range of internal short circuit faults. The initial work outlined provides the basis for deeper analysis of measurement parameters and how they can be used to help define faults conditions. Considering the first set of simulations reported, the input current can be used as the main indication for primary winding short circuits. Output voltage and input current are considered to be strong contenders to detect the secondary winding faults. It has been shown fault type is more easily determined than fault location, as location does not affect the measurable parameters considered. Considering the second set of simulations reported, a short circuit between two windings can be detected using the output voltage and the value gained does give information on fault location.

The measured parameters can be used to indicate faults that may occur between sections and between windings of a power transformer during the normal operation.

The ability to define fault severity from external, on-line measurements will be of great interest to power transformer owners and operators.

Future work will consider more complex modelling of the transformer windings and compare practical tests with the simulated values indicated in this work.

ACKNOWLEDGMENT

The authors would like to thank the School of Engineering & Built Environment, Glasgow Caledonian University for providing the facility for the research.

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