CHAPTER -7

CONCLUSIONS

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Power transformers are key components in electric power systems and unplanned outages can result in considerable cost and disruption. It is extremely essential to identify transformer problems at an early stage before a catastrophic failure occurs. Conventional techniques may detect the winding displacement or deformation if only a displaced or slack winding gives rise to secondary fault such as partial discharge or overheating. Frequency Response Analysis (FRA) is the most effective diagnostic tool for detecting mechanical displacement and deformation of windings inside a transformer.

There is not any traditional method available to detect the deformation. Conventional methods of diagnostic tests like ratio and winding resistance method, impedance/inductance measurement, magnetizing current measurement etc may not detect winding deformations in transformers. Short circuit Impedance method is most widely accepted method, currently specified in short-circuit test standards. It requires relatively simple equipment. In this method reference results from tested equipment are used for comparison. The disadvantage of this method is that even very small changes are significant and limited sensitivity for some failure modes. The main methods of detection of winding deformation/displacement are Impedance (leakage reactance) measurement, Low Voltage Impulse (LVI) method and Frequency Response Analysis (FRA) method.

Deformation results in relative changes to the internal inductance and capacitance of the winding. These changes can be detected externally by the frequency response at the terminals of transformer winding. Electrical changes, corresponding to mechanical deformations can be observed in measured frequency responses. Many researchers have been involved in studies on diagnostic and interpretation of Frequency Response Analysis (FRA) data in the last decade.

Many researchers have been involved in studies on framing the interpretation of guide lines for various deformations in transformer windings based on Frequency Response (FRA) data. There are no standards for interpretation of FRA to unambiguously detects winding deformation/displacement. It is also required to apply latest techniques like numerical tools, transfer function parameters and ANN to improve the interpretation and diagnose the faulty winding, using FRA data.

FRA technique using Sweep Frequency Response Analyzer (SFRA) is used in detection of transformer winding deformations. Research work is carried out for various deformations simulated experimentally on transformer windings to analyze the frequency responses. The frequency responses are analyzed for their sensitivity to detect and identify the faulty winding. Numerical techniques are applied to help in detecting the deformations in the windings of transformer. FRA data obtained on various transformers at site is also used to interpret transformer winding faults.

Investigations on various aspects of frequency response measurements for various test conditions have been performed to measure frequency responses. Sensitivity of various test conditions for detecting winding deformations for application to site measurements has been looked into. Investigations are carried out, experimentally, for various deformations, simulated on transformer winding and the impact of various parameters that influence the frequency response is studied. The information obtained through such investigations is used for diagnosing the integrity of transformer windings.

In this work, various deformations are simulated on model transformer to analyze the frequency responses. The frequency responses are analyzed for their sensitivity to detect and identify the faulty winding. Few numerical techniques are used for interpretation and detection of winding deformations. Numerical techniques for interpretation of FRA measurement data obtained from site are also applied to detect and diagnose the faulty windings. The transfer function is estimated from the FRA data to find the transfer function parameters such as poles, zeros, natural frequencies of poles and zeros, damping coefficients of poles and zeros and gain to interpret the winding faults. The transfer function data is used to train the ANN. An attempt has been made to apply the ANN technique to diagnose and identify the type of fault. The conclusions drawn from the various studies to formulate interpretation guidelines for assessing the mechanical integrity of the transformers are given in the following sections.

1. **Experimental investigations to identify SFRA measurement sensitivity for interpreting faults.**

Investigations were carried out on 1 MVA, 11 KV/433V delta-star 3 phase transformer to study the frequency response sensitivity to various test configurations. It was observed that, the frequency responses with terminal floating are very sensitive for inter phase measurements, to detect the deformations in the windings. Most of the configurations indicate a problem in the transformer. However, to identify the particular winding it is found essential to analyze all the plots of frequency responses. The frequency responses which are giving higher degree of variation from the reference can be confirmed as a faulty winding. It was observed that, end to end (open) frequency responses are very sensitive to detect the faults within the windings. It is concluded that the tests with end to end (open) measurements, inter turn fault and disc fault shows considerable shift in the frequency range up to 40 KHz. For delta connected windings, the fault in HV winding will also result in variations in LV winding responses. Change in winding self capacitances in a transformer is found to have resulted in significant changes in frequencies between 150 to 650 kHz with end to end (open) measurements. It is also observed that, end to end (open) responses are sensitive in medium frequency range and capacitive inter winding responses are sensitive up to 200 kHz for axial displacement type of faults in a transformer.

For radial displacements, shift in the resonant frequencies are observed in from about 200 kHz to even up to 1 MHz suggesting significant contribution of both inductive and capacitive component for end to end (open) test configuration. It is also observed that the frequency response with radial displacement fault largely deviates from its base response uniformly throughout from 2 kHz to 1 MHz for end to end (open) measurement responses. Frequency responses in inductive inter winding and capacitive inter winding test configurations were insensitive to detect the radial displacements. With end to end (open) test conditions. A small shift in frequency responses throughout up to 2 kHz was observed for core earthing irregularities.

However, the impedance measurements carried out for different fault conditions did not show enough sensitivity at 1 KHz frequency to detect the fault except in the case of turn and disc faults. It is also observed from the analysis of results that, under different simulated fault conditions, FRA with different test configurations can form a better tool in assessing the integrity of transformer.

2. **Application of numerical techniques for interpretation of FRA data for diagnosing integrity of transformer**

Experimental investigations were carried out to obtain end to end (open) measurement FRA data from a transformer for various simulated faults. Application of numerical techniques for detecting different types of transformer faults from the FRA data obtained for various test configurations are discussed. Realistic Numerical Parameters were evolved based on the comparison of parameters for sister units, outer windings, and similar design windings in the three bands are given in Table 7.1. Percentage variation of the numerical parameters Viz., MM, MSE, MABS, ASLE, SD and CC were computed by comparison with the realistic numerical values presented in Table 7.1. in three different frequency bands, for various simulated faults to evolve them for interpretations in assessing the condition of the transformers.

Table 7.1: Critical realistic numerical parameters to diagnose integrity of transformer

Numerical Techniques	Critical Realistic Parameters		
	Band-1 (20 Hz -10 kHz)	Band-2 (10 kHz-100 kHz)	Band-3 (100 kHz-1 MHz)
CC	0.998	0.991	0.975
MSE	0.8	0.9	3
ASLE	0.15	0.4	0.8
MABS	0.7	0.8	1.8
MM	1.01	1.02	1.08
SD	8	10	12

It has been found that inter turn fault and disc faults are more or less similar and it is very difficult to distinguish them. For inter turn type of faults, end to end (open) connection, all parameters show significant deviations in band-1 and appreciable deviations are also extended in Band-2 for all the parameters except MM. In disc and inter turn faults MSE, RMSE, MABS show significant percentage deviation in Band-1 and Band-2 but all the numerical parameters for end to end (open) LV side have also resulted in corresponding percentage deviation from realistic ideal values. This may be because of the delta connected HV winding.

Small percentage changes in low frequency band whereas considerably large percentage variations in the responses in higher frequency bands is observed in winding deformation faults. End to end (open) test condition is found to be more sensitive for the capacitive changes with observed changes are more significant in higher frequency band i.e. band 3, for the transformer winding as compared to other test conditions. It is also observed that all parameters are showing deviation in Band-2 and Band-3 but much variation is found in Band-2. It is concluded that, end to end (open) measurement can be used to determine winding deformation/displacement fault and the deviation is mainly seen in Band-2 and Band-3 frequency bands.

Only Band -1 numerical parameters found to have deviations from the realistic values for improper core earth type of deformities. It is also seen that most of the numerical parameters do not change significantly or abruptly as compared to other type of deformities/displacements. End to end (open) measurement is found to be the best measurement to predict this type of fault.

For axial displacement type of fault, all numerical parameters except MM show positive deviation in Band-2 and Band -3. In axial displacement, end to end (open) and end to end (short) measurement show major deviation in Band-3. It is also concluded that, axial displacement fault can be easily determined by end to end of LV side measurement case and there is change in more number of numerical parameters in higher frequency band.

All the numerical parameters except MM show the tendency of positive variation in all the three bands for radial displacement type of fault. In addition, it is also observed that, Band-2 parameters have larger deviation as compared to Band-1 and Band-3 parameters.

SFRA data obtained at site on the number of transformers were analyzed, using the numerical parameters computed in the three frequency bands to investigate different type of problems. It was observed that for winding deformation and shorted turns, band 1 parameters show considerably large deviation when compared to critical values given in Table 7.1. For the open circuit/ OLTC contact open case, abnormal change in band 1 and band 2 parameters, when compared with the realistic values given in table 7.1, as against the normal deviation due to position of the tap switch was observed. It can also be observed that ASLE and CC parameters in band 1 are very much away from the normal values given in table 7.1 indicating core related problem. It was also observed that, for major winding movement/displacements, band 3 numerical parameters are considerably higher than the numerical parameters given in Table 7.1. It is thus observed that, exceeding the numerical parameters given by this table is an indication of deformation/displacement in the transformer by considerable degree and necessary action has to be taken. The numerical parameters given in table 7.1 can thus be used to set the tolerance limits after accounting for manufacturing differences and asymmetry of the winding to diagnose the condition of the transformer. It can also be used to discriminate the faulty winding and type of fault based on the interpretation guidelines presented on the variation of these numerical parameters in different frequency bands.

MSE, MABS doesn't give exact results as they vary largely even if there is small deviation in the peaks. MM is observed to give ambiguity in some interpretations. CC, ASLE and SD parameters are observed to be giving consistent interpretation when all parameters are compared for finding faults. However, more data on the FRA investigations are needed to identify the problem and validate the interpretation with physical verifications of the transformer. The disadvantage of the numerical parameter approach is that the two sets of data shall have the same format for computing the parameters. However, it is felt that interpretation done using a single parameter may be lead to an underestimation or exaggeration of isolation deviations present in the data. Therefore, it is preferred to use a set of numerical parameters in a complementary way to get diagnostic conclusion.

3. Conclusions drawn from distinguishing changes obtained in the transfer function parameters for different faults are as follows

Experimental investigations were carried out on a transformer to obtain frequency response data under physically simulated fault conditions. The transfer function and its characterizing parameters were computed for various fault conditions using real rational polynomial technique. Effectiveness of these parameters for various faulty conditions for detection of transformer winding faults was studied. The conclusions drawn from the distinguishing changes in the transfer function parameters for various types of faults are listed below:

Interturn faults

- The change in gain is almost negligible (negligible change is ± 10 dB).
- Lower frequencies of both poles and zero locations of the faulty phase response are influenced.
- Middle position inter-turn deformation fault is found to have more shifts than top and bottom, in both poles and zeros.
- Damping coefficient change at the natural frequency location, where major shift of poles and zeros occurs, at middle position is found to be exactly reverse as compared to top and bottom position.
- No specific trends in TF characterizing parameters that could suggest the possibility of identifying the position of the deformation/displacement.

Minor winding deformation faults

- For minor winding deformation faults, behavior changes in TF characterizing parameters similar to that of major deformation fault is observed for this minor winding deformation faults .
- However, higher shift in frequency locations of both poles and zeros as compared to major deformation faults was observed.
- In addition to that, new poles and zeros are neither created nor eliminated and higher percentage shift of natural frequency of pole and zeros is observed.
- For minor winding deformations, new poles and zeros are neither created nor eliminated and higher percentage shift of natural frequency of pole and zeros is observed.

Axial displacement faults

- For axial displacement faults, LV winding phase response at higher frequencies of zero locations and HV winding phase response at higher frequency of pole locations are influenced.

- Maximum increment in gain was seen with HV-Y phase response of axial displacement faults, whereas, maximum decrement in gain has occurred with LV-y phase response for axial displacement faults.

- Poles and zeros at certain locations of both HV and LV winding transfer function are influenced (i.e. above 2% change) for frequencies above 200 kHz.

- The damping coefficient of all pole locations above 200 kHz for both HV and LV winding TF only are highly influenced.

- The damping coefficient of all zero locations for both HV and LV winding TF are not influenced.

- The maximum change in the absolute value of overall gain for HV and LV winding transfer function.

Radial displacements

- For radial displacements of HV winding, large shift occur for majority of natural frequencies of both poles & zeros and major change in damping factor for all the poles and zeros occur. Additionally, maximum of extra new poles and zeros are created.

- All outer (HV) winding open end responses result in addition/deletion of majority of pole locations at lower frequencies ie <10 kHz. However, in medium frequency (10 kHz-200 kHz) range, majority of poles and zeros change more than 2%.

- Similarly, all inner (LV) winding open end responses result in a majority of pole locations being added / deleted for lower frequencies ie below 10 kHz. In addition, the change in gain is observed to be more when compared with outer HV winding response parameter.

- HV winding end to end (short-circuit) measurement response result in no change in both pole and zero locations at lower frequencies (<10 kHz). However, for frequencies above 10 kHz and up to 1 MHz, both poles and zeros locations have similar behavior that is observed with open end to end responses.

- Capacitive inter-winding measurement responses result in addition or deletion of majority of pole locations for frequencies below 10 kHz and frequencies above 1 MHz. For frequencies above 10 kHz and up to 1 MHz, majority of poles and zeros do change more than 5%.

Core related faults

- For core related faults, behavior changes in TF characterizing parameters similar to that of deformation faults are found. However, less shift in frequency locations of both poles and zeros as compared to inter turn deformation faults was observed. For LV-y response of pole locations have more impact than that of HV-Y response. For core faults, HV response parameters at higher frequencies of pole locations and LV phase response medium frequencies of pole locations are influenced.

4. Application of Artificial Neural Networks for interpreting frequency response measurements study lead to following conclusions:

Application of Artificial Neural Networks for interpreting frequency response measurements was studied. In this work, deformations and displacements were simulated experimentally on model transformer windings to obtain the frequency response data. The transfer function and its characterizing parameters were computed for various fault conditions. Through the estimation of transfer function of an FRA plot, the parameters of the transfer function, i.e., the gain, the zeros, and the poles were used to diagnose the winding deformation. These parameters are then used to train ANN to find out the possibility of identification and classification of faults. An Artificial Neural Network (ANN) based algorithm for detection of transformer winding faults is studied using simulated test data of deformation and displacements. The predicted fault closely matches the created fault suggesting the effectiveness of the model. It was thus observed from the study that, Identification of different types of winding faults may be possible through studying and training the ANN for various frequency response signatures using frequency response database.

The results and information presented from the various investigations carried out in the research work will be useful in forming interpretation guidelines using Sweep Frequency Response Analysis (SFRA) method for its application in assessing the mechanical integrity of the transformers. However, further work needs to be carried out to classify the severity and location of faults.

7.2 SCOPE FOR FUTURE WORK

Further investigations are needed to classify the severity and location of fault from the estimated transfer function parameters. The fault identification can be automated using ANN technique, if large amount of FRA data along with fingerprints for different types, location and severity of the fault is available. Further work in this direction can be undertaken to classify the severity and location of fault from the estimated transfer function parameters using ANN, fuzzy logic etc techniques.