International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 7, July - 2014

Determination of Fault in 500 kV Converter Transformer Based on Coherence Function Analysis of Neutral Current

Malapati Nandith Reddy
Department of EEE
St. Martin's Engineering College
Hyderabad, India

T. Sunny Moses
Department of EEE
St. Martin's Engineering College
Hyderabad, India

B. P. Singh
Director (R&D)
St. Martin's Engineering College
Hyderabad, India

***Abstract*— Long distance power transmission from the point is carried out by an HVDC system. The first HVDC system introduced in India is about 925 K.M long between Rihand and Delhi with a power evacuation capacity of 1500 M.W with a ± 500 kV. D.C. Converter transformers at this voltage are always at a risk of failure due to internal and external over voltages. In order to test a transformer, Comparison of neutral current at standard reduced and full impulse voltage is carried out. During turn failure the detection of turn fault merely by eye estimation is fraught with uncertainty. Hence, new diagnostic methods have been published and are used by several testing agencies. They are based on Frequency Response Analysis, Wavelet Analysis and Coherence Function Analysis. The present work deals with the analysis of fault using coherence function between neutral currents with and without fault. In order to simulate the problems, the converter winding is divided into a number of sections. Each section is represented by self and mutual inductances as well as Inter disc capacitances and capacitances to ground. Appropriate equations are developed to calculate current for a given impulse voltage at the high voltage terminal. The converter winding of the transformer is subjected to an impulse voltage of unit value and neutral current is calculated. Turn faults are simulated by reducing the number of turns at appropriate coil depth (CD) of the winding. The two neutral currents are analyzed with Frequency Response and Coherence Function. It is observed that, although Frequency Response Analysis (FRA) also indicates the change in frequencies, sensitivity of Coherence is high for all cases considered. The results presented depict the neutral current comparison, Frequency Response comparison and Coherence Function (CF) comparison for 1turn, 5turn and 10 turn failure in top few sections of the transformer. The results suggest that the fault can be clearly detected using CF technique.**

***Index Terms*— Coherence Function (CF); Frequency Response Analysis (FRA); Converter Transformer; Neutral Current; Impulse Voltage; Power Transformer Diagnostics.**

I. INTRODUCTION

As per the standard requirement, a power transformer should go through impulse test and comply with the condition for meeting the test conditions. The voltage level that a transformer should successfully withstand depends on its voltage rating. It consists of a series of test voltages i.e. reduced lightning voltage for standardization, followed by full lightning voltage and chopped voltage. In each application, the current is recorded and examined for any difference between current with reduced and full voltage.

It has been an understanding that for minor failure like turn to turn, visual assessment of neutral current occasionally leads to flawed conclusions. Since, there are significant economic considerations pertaining to power transformers, the acceptance or rejection, merely by visual observation of neutral current could not be fully justified. On the other hand, no conclusive method to estimate the failure or otherwise exists so far. Therefore, diagnostic methods are required to be developed to establish the condition of a transformer with a reasonable confidence after completion of impulse test. In light of this, Frequency Response Analysis (FRA) method attained significance with testing agencies and services all over the world.

The FRA is based on the principle of change of frequency due to change in inductance or capacitance of the transformer under test. Higher changes like winding movement, core movement or winding faults can be detected easily, since it produces a significant change in current shape and magnitude. In most cases, these changes may lead to variation of voltage shape as well. However, single turn fault may lead to insignificant variation in shape and magnitude. Besides, the Frequency Response diagnostic is not very effective in detecting turn fault, since the variation in frequency occurs at a relatively higher frequency and hence may get buried in the noise. Advanced method was suggested using Wavelet Techniques, since wavelet is characterized by its capability to analyze the signal in time-frequency domain. Wavelet Technique is implemented by analyzing current at reduced voltage and full voltage. To carry out the analysis, each dominant frequency is converted into time response using appropriate Mother Wavelet. Based on the difference in time-frequency characteristic for neutral currents at reduced and full voltage the failure is detected. However, this could not possibly provide stand alone method of detecting failure and was complimented by both neutral current comparison and FRA.

In order to obtain still further clarity in fault detection, some authors published work on Coherence Function Technique. All work investigated and published do not fully enlighten on the type of fault which could have occurred within. However, there was a general agreement in work published that no single type of analysis can conclusively isolate turn fault. However, a combination of the outcome of all the techniques collectively could be considered for the detection of turn fault. The present work also reports the research carried out with CF application. Three transformers of 400 kV class impulse tested at manufacture's work were taken up for detailed analysis. The neutral current of the high voltage winding was recorded and coherence of current at reduced and full impulse voltage was determined. Out of the three transformers analyzed, two pertain to result which had passed the impulse test at 1.2/50 µsec, 1425 kV, while one of the transformers had failed during rated lighting impulse test.

The comparison of analyzed data between the failed and passed transformers is expected to reveal the precise difference between the behavior of CF. In addition, it could also reveal the presence of partial discharges between reduced and full voltage tests, if any. To understand the mechanism, certain theoretical calibration studies were also done by superimposing noise of known types on impulse voltage and evaluating the coherence between the two signals. The paper presents a detailed analysis of coherence for the neutral current of power transformers discussed above and possible reasons for differences in coherence.

The present report deals with the analysis of fault using coherence function between neutral currents with and without turn fault. In order to simulate the problems, the converter winding is divided into a number of sections. Each section is represented by self and mutual inductances as well as Inter disc capacitances and capacitances to ground. Appropriate equations are developed to calculate current for a given impulse voltage at the high voltage terminal. The converter winding of the transformer is subjected to impulse voltage of unit value and neutral current is calculated. Turn faults are simulated by reducing number of turns at appropriate Coil Depth (CD) of the winding. The two neutral currents are analyzed with Frequency Response and Coherence Function. It is observed that, although Frequency Response Analysis (FRA) indicates the change in frequencies, sensitivity of Coherence is high in all cases considered. The results presented illustrate the neutral current comparison, Frequency Response comparison and Coherence Function (CF) comparison for 1turn, 5turn and 10 turn failure in top few sections of the transformer. The results imply that the fault can be clearly detected using CF technique.

II. THEORY OF COHERENCE FUNCTION

Coherence Function offers information concerning the linear dependence between the two signals as a function of frequency. The theory of CF is given below. If f (t) and g (t) are the input and output signals of the system and F (f) and G (f) the related Fourier transforms. Then, the CF γ^2 (f) is mathematically defined as:

$$\gamma^2(f) = \frac{|S_{FG}(f)|^2}{S_{FF}(f).S_{GG}(f)}$$

Where,

S_{FG} (f) = Cross Power Spectrum between the excitation and response signal

S_{FF} (f) = Power Spectrum of the excitation Signal

S_{GG} (f) = Power Spectrum of the response signal

CF is a plot of magnitude with the frequency of a time function and shows the frequency at which the coherence is the highest and the frequency at which it is least.

Value of Coherence Function is unity if the two outputs from a system of linearly related inputs are equal. If there is any delay or distortion in response signals then the values are less than unity. Values of the coherence function less than one are possible in the event of non correlated noise, circuit failure, partial discharges and non-linearity in the system.

III. TRANSFORMER MODELING AND DESIGN PARAMETERS

A 315 MVA 500 kV Converter transformer as shown in Fig.1 is considered for theoretical analysis. The HV winding has 4 sections in all. The Converter winding or the D.C. Coil has been divided into 16 sections for simulation purpose.

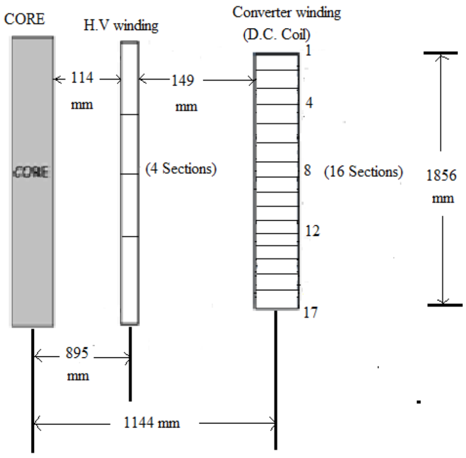

Fig.1. Schematic Diagram of a 315 MVA 1-Ø Converter Transformer

The high voltage winding has 4 sections along the Coil Depth (CD). The total height of Converter winding is divided into 16 suitable non-uniform sections. The distance between Core and HV Winding is shown as 114 mm. And the distance between HV Winding and Converter Winding is taken to be 149 mm. The height of the Transformer is 1856 mm. Self inductances, mutual inductances between sections, series and shunt capacitances are calculated by using a standard formula. An equivalent network is derived based on the above values as shown in Fig 2. The capacitance between HV and LV winding is distributed along the height of the winding in proportion to the height of each section. The capacitance in parallel with each section is calculated based on the number of discs in the series in a section. A standard unit impulse voltage is applied at HV terminal.

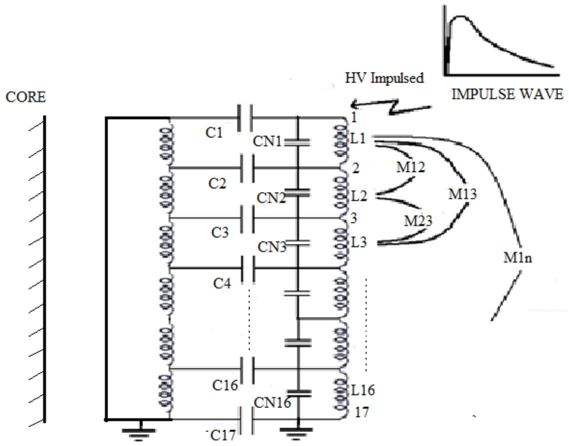

Fig.2. Electrical Equivalent circuit of 315 MVA HVDC Transformer

The CF is determined by using two output neutral currents a) without turn fault b) with turn fault. The CF calculation is based on the fact that for a given input; output characteristic remains unaltered for an electric circuit and that the output can vary only in the event of either (a) source property is changed or (b) the circuit parameter undergoes variation. Thus, the equation for coherence, for the present analysis can be derived on the basis of input and output parameters. If it is considered that for a given input f (t) to a circuit, the output is g (t) and for a fault in the circuit the output is h (t) and their Fourier transforms are G(f) and H(f) then,

$$\gamma^2(f) = \frac{|S_{GH}(f)|^2}{S_{GG}(f).S_{HH}(f)} \qquad (1)$$

Where,

γ^2(f) = Coherence Function

S_{GH} (f) = Cross Power Spectrum between the output signal with and without Turn fault.

S_{GG} (f) = Power Spectrum of output signal without Turn fault.

S_{HH} (f) = Power Spectrum of output signal with Turn fault.

Thus, the coherence is represented by the real part of equation 1.

IV. RESULTS AND DISCUSSION

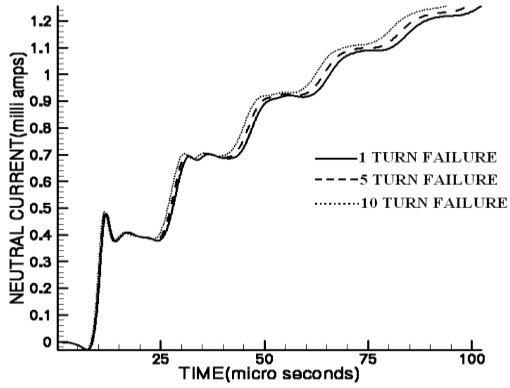

Fig.3. Time Vs Neutral Current for various turn faults in section1 of a Converter Transformer

As the Turn failure increases, the difference in neutral currents also increases due to larger changes in inductances and capacitances. It is inferred from Fig.3 that Turn failure has a corresponding effect on neutral current, magnitude associated with frequencies and Coherence Function. The effect was examined for Various Turn failures from 1 to 10 in the steps of 1.

Table.1. Neutral Currents for different turn faults at an instant of 50µs.

Turn Fault (No. of Turns)	Neutral Current (ma)
No Turn Fault	0.882
1	0.887
5	0.909
10	0.927

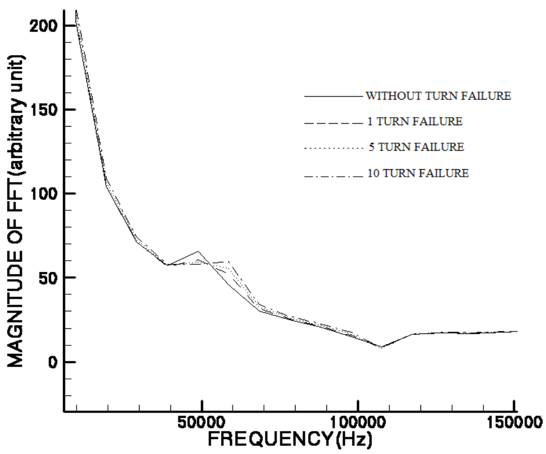

Fig.4. Frequency Vs Magnitude of FFT for various turn faults in section 1 of a Converter Transformer.

The FFT plots for the obtained neutral currents are shown in Fig. 4. A close examination shows a small difference in the FFTs with and without turn failure. This is to say that with the increase in the turn failure, the magnitude of FFT does not show a significant change. In view of this, it can be said that FFT analysis of faults is fraught with less sensitivity.

Table 2 Magnitude of FFTs for various turn faults in section 1 of a Converter Transformer.

Turn Failure	Freq f_1 (kHz)	Magnitude of FFT (arbitrary unit)
1	107	8.135
5	107	8.08
10	107	8.87

Table 2 shows the magnitude of FFT for various turn failures in at a dominant frequency of 107 kHz.

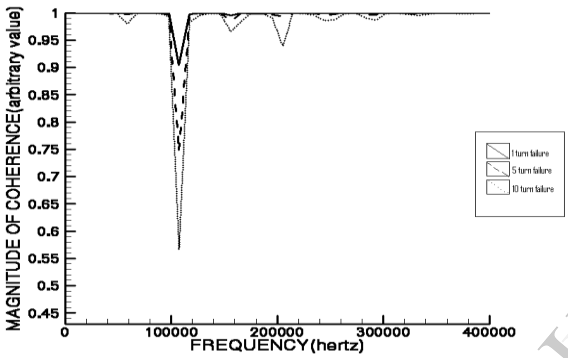

Fig.5. Frequency Vs Magnitude of Coherence for various turn failures in section 1 of a converter Transformer

It is inherent from Fig.5 that the Magnitude of Coherence varies with the number of turn failures. And greater the turn failure, greater is the deviation from the desired magnitude i.e. unity.

For instance, let us consider a random section in the Converter Transformer. If we take a 1 turn failure the Magnitude of coherence is found to be 0.945 which has a less deviation from the desired magnitude i.e. unity. Similarly when we consider 5 turn failure, the Magnitude of Coherence is found to be 0.745 which has furthermore deviation from the desired Magnitude. Furthermore, if we consider 10 turn failure the Magnitude of coherence is found to be 0.566.

Table 3 Magnitude of coherence for various turn failures in section 1 at a dominant frequency of 107 kHz

Turn Failure (No of turns)	Freq f_1 (kHz)	Magnitude of CF
1	107	0.945
5	107	0.745
10	107	0.566

Table 3 shows that, as the turn failure increases, the Magnitude of CF decreases i.e. more deviation from the desired value of unity.

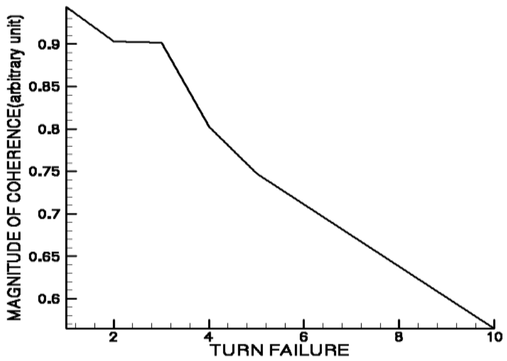

Fig.6. Turn Failure Vs Magnitude of Coherence in section 1

Fig. 6 shows the graph for the turn failure and the corresponding change in the magnitude of Coherence. A steep decline in the magnitude can be observed with the increase in turn failure.

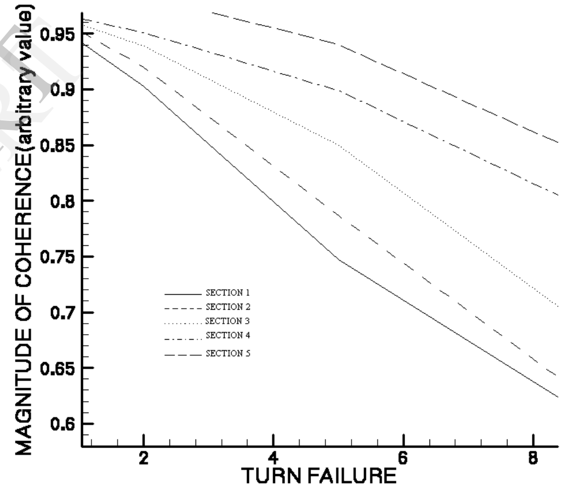

Fig.7. Turn Failure Vs Magnitude of Coherence in top few sections of a converter transformer

Table 4 Turn failure Vs Magnitude of Coherence in top few sections at a dominant frequency of 107 kHz.

Turn Failure	Magnitude of CF (Section 1)	Magnitude of CF (Section 2)	Magnitude of CF (Section 3)
1	0.944	0.953	0.959
5	0.747	0.787	0.85
10	0.565	0.572	0.636

The above graph in Fig.7 and table 4 give the Magnitude of Coherence and their dip for various turn faults in top few sections of a Converter Transformer. It can be clearly seen that, as the turn failure increases, there is a significant change in Coherence. It can be observed that, greater the turn failure, lesser is the Magnitude of coherence and deviation of Magnitude from the desired value is more. The desired value being unity.

CONCLUSION

The work reported in this paper deals with the variation of neutral current, frequency response and CF for a Turn fault variation of winding of 315 MVA 500kV Converter Transformer. It is shown that with the small Increase in Turn faults, the CF varies significantly. This method may be used in detecting small variation in the Turn faults of winding structure.

All in all, from the results it can be concluded that the Coherence Function is more sensitive to faults and the faults can be diagnosed easily with the help of coherence function.

ACKNOWLEDGMENT

The authors are thankful to the management of St. Martin's Engineering College and Prof. K. Shashidhar Reddy HOD-EEE department for providing the resources to carry out research and permitting to publish this work.

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