# Analyzing Transformer Core Faults by using Real-Rational Polynomial Function Model From FRA Data

**K. Sahitya Yadav, K. Sumanth**

***Abstract*— *The paper presents the results of the experimental investigation carried out on a transformer to obtain frequency response data under core faults. These core faults were physically simulated to study and identify the various parameters that influence the frequency responses. Transfer Function using real-rational polynomial function model was computed from the frequency response data. Various transfer function parameters were computed for reference and simulated faulty frequency response data. These parameters are then analyzed to relate changes to characterize the defects. The analysis presented based on the transfer function characteristic parameter changes will help in diagnosing transformer core faults.***

***Index Terms*— *Frequency Response Analysis; Real-rational polynomial; Transfer Function; core faults.***

## I. INTRODUCTION

Power transformers are the most important and expensive component of the energy system. An unexpected outage of a power transformer results in substantial costs mainly caused by the outage of the power station. Demand on monitoring and diagnosis of such costly equipment is increasing due to their strategic importance for reliability of power system. One of the most common and direct damage is deformation of the windings. These are caused by enormous electromagnetic stresses experienced by transformer due to large short circuit currents. Once a winding is deformed, the ability of the transformer to withstand further short circuits reduces resulting in failure of the transformer. Hence, it is essential to monitor the health of the transformer by conducting diagnostic tests. Frequency Response Analysis (FRA) has been widely used for diagnosing deformations of the transformers [1-4]. In CIGRE SC-12 Budapest Colloquium [5], it is reported that some interpretation of FRA results are not so clear and failure criteria is uncertain. However, there are no systematic guidelines for interpretation of the FRA results and more needs to be studied, collect data by conducting experiments on model transformers or measurements at site and analyze them for an objective and systematic interpretation methodology. Deformation of

transformer windings results in the changes in capacitance/inductance of the transformer network model, which modifies the frequency response transfer function when compared with healthy transformer. FRA measurement results can be used to construct transfer function model of the transformer [6]. The status of the winding can be diagnosed by examining the changes in the transfer function parameters when compared with the healthy (reference) transformer parameters. In the present work, experimental investigations were carried out wherein frequency responses were obtained under core faults simulated on a transformer core and coil assembly. Mathematical Transfer Function (TF) using real-rational polynomial function model algorithms was computed from the SFRA data. TF characterizing parameters like natural frequency of oscillation and damping coefficients of poles and zeroes were computed for reference and simulated faults. These parameters are then analyzed to relate changes to detect the defect. Results of the investigations presented in this paper will help in diagnosing transformer core faults.

## II. EXPERIMENTAL METHODOLOGY

Figure 1 show the core and coil assembly of a 1000kVA, 11kV/433V, three phase, and Delta/star transformer used as a test specimen along with Sweep Frequency Response Analyzer (SFRA) used as a measuring instrument to obtain the data in this study. SFRA instrument is provided with inbuilt processor for data storage, processing and display. The instrument comprises of one analog sweep frequency voltage source, which gives output of 10Vp-p at 50 ohms, and two input channels that are simultaneously sampled. The instrument has a frequency range of 10 Hz to 10 MHz with logarithmically spaced steps. The automatic scaling feature of the range based on the input magnitude level gives very good dynamic range.

The data is displayed as Frequency versus Magnitude and Phase. The signal cables are shielded 50 ohms measuring cables. The SFRA test requires a 3-lead approach, with the leads providing signal, reference and test. This approach means that signal put into the test winding is itself taken as reference. This reference is compared with the signal, which emerges at the far end of the winding and is measured by test lead. Figure 2 shows the schematic of the SFRA measurements on transformers.

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**Figure 1.** A view of test specimen along with SFRA

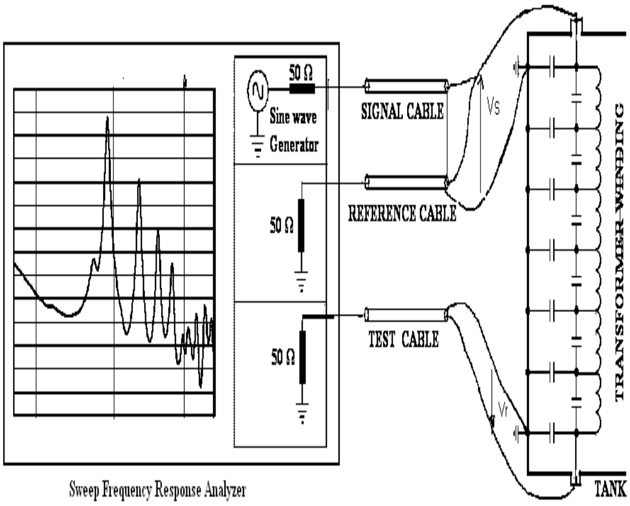


**Figure 2.** Schematic of the experimental set up for SFRA measurements.

One of the common types of test connections, which are found to be very sensitive to different type of faults in a transformer, employed in SFRA measurement is end-to-end (open) measurement.

**End-to-end (open) measurement**:

In end-to-end (open) test configuration, the input signal is applied to one end of the winding and the transmitted signal at the other end of the same winding is measured. All other terminals of the transformer are left open as shown in figure 3. Core faults were simulated Y phase (middle limb) of HV winding and denoted as HV-Y and LV winding and denoted as LV-y for this measurement.

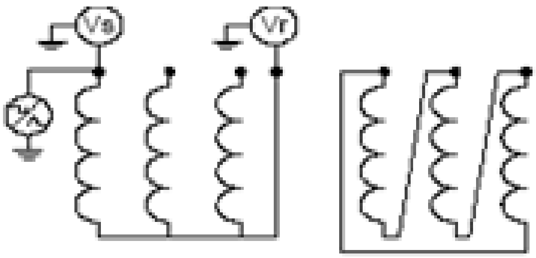


**Figure 3.** End-to-end (open) measurements.

## III. COMPUTATION OF TRANSFER FUNCTION AND ITS CHARACTERIZING PARAMETERS

To determine the system parameter and structure, the frequency response can be expressed by a transfer function of the form:

$$F(s) = \frac{p(s)}{q(s)} = \frac{b_n.s^n + b_{n-1}.s^{n-1} + ..... + k + b_0}{a\ .s^n + a_{n-1}.s^{n-1} + ..... + k + a_0} \quad ..\ (1)$$

The FRA measurement data obtained was used to compute the transfer function based on real-rational polynomial function model. MATLAB function invfreqs [8] was used for converting magnitude and phase data into transfer functions. Simple linear least-square estimates and non-linear estimates were used in this function. MATLAB function freqs [8] returns the complex frequency response from the transfer function. The calculated frequency response data is compared with the measured data to obtain the best fit. Figure 4 shows the measured frequency response and calculated frequency response for magnitude plot of HV winding of the transformer achieved with 19 poles and 17 zeros.

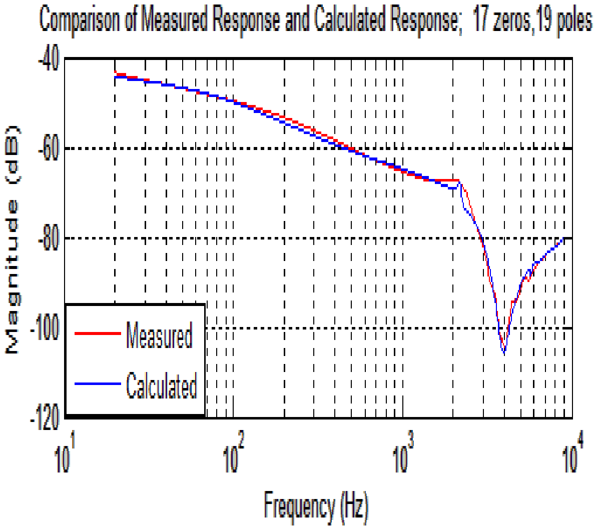


**Figure 4.** Measured and calculated magnitude response of transformer winding.

It can be observed from the figure that, calculated frequency response from the best fit transfer function for 19 poles and 17 zeros closely matches with the measured response. Similarly, the best fit TF were computed for different type of winding connections, considered in this study, for further analysis.

The estimation algorithm determines the poles and zeros from both the magnitude and phase angle using MATLAB functions DAMP and ZERO [8]. The pole (P) and zero (Z) are given in the complex form as in equation 2. The damping coefficient (δ) is calculated using equation 3 and change in gain (k) in dB is calculated using equation 4.

$$P(or)Z = -\alpha \pm j\omega_n \quad (2)$$

$$\delta = \alpha / \omega_n \tag{3}$$

$$\Delta .k = 20\log(k_{def}) - 20\log(k_{ref}) \tag{4}$$

Where α is the real magnitude and ωn is the natural frequency of the corresponding pole or zero. The transfer function parameters, and their relative changes depend on the type of fault. The transfer function fitting is obtained by real rational polynomial method and the parameters of the transfer function are used for further analysis.

## IV. RESULTS AND DISCUSSION

Base reference response of the transformer windings for without simulation of a fault for the measured test connection is compared with magnitude response for a particular type of simulated fault. End to end frequency responses of the middle limb are only considered for computing the parameters for analyzing the behavior, as the various type of faults were created in the middle limb. The behavior of any system depends on its poles and zeros, its numbers and relative positions. The comparison is made between reference (base) and core faultsTF parameters obtained from the best fit transfer function. Once the suitable transfer function is found the parameters of the TF viz. poles, zeros, natural frequencies and damping coefficients of both poles and zeros can be obtained. The fault causes creation and elimination of poles and zeros, shifts in absolute frequencies of poles and zeros and changes in gains which can be analyzed to diagnose the fault.

In order to study the sensitivity of frequency responses for identifying the improper core earth related issue of the transformer, copper strip connection of core to earth was disconnected as shown in figure 5, and here one type of measurement i.e. End-to-end (open) measurement (HV-Y,LV-y) was considered for this core fault.

Figure 6 shows the measured magnitude responses of reference (base) and core fault from HV-Y limb FRA data. Table 1 gives the computed components of poles and zeros for transfer function of reference (base) and core fault from HV-Y limb FRA data.

Figure 5. A view of test specimen with core faults.

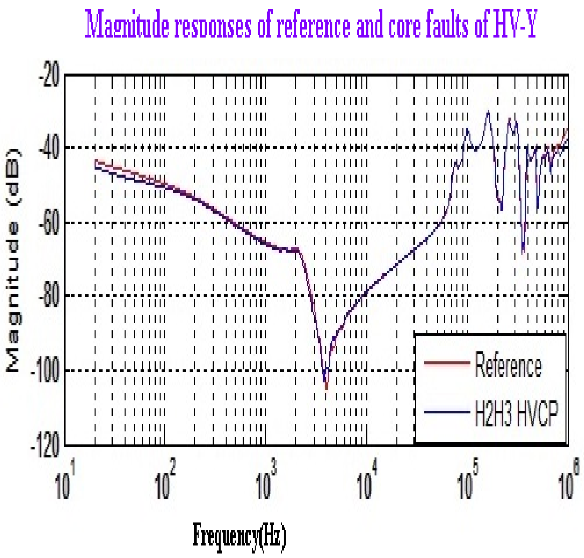


Figure 6. Magnitude responses of reference and core faults of HV-Y.

It is observed that from Table I, one new real pole at 0.076M rad/sec, one complex pair of poles at 0.073M rad/sec, two real zeros at 9.92M rad/sec, -1.67M rad/sec and one complex pair of zeros at 6.24M rad/sec is created. One real pole and zero, one complex pair of zeros and poles are eliminated. Major shift occurs at 7.61M rad/sec to in poles and at 0.09M rad/sec in zeros. Among the poles, highest shift is about 9.56% at 7.61M rad/sec, whereas in zeros highest shift is about 15.29% at 0.09M rad/sec. TF parameters obtained for HV-Y FRA data indicate large shift occur only around for natural frequencies at 2M rad/sec of poles and zeros. Major change in damping factor is observed for all poles only.

Figure 7 shows the measured magnitude responses of reference (base) and core fault for LV-y limb FRA data. Table II gives the computed components of poles and zeros for transfer function of reference (base) and core fault from LV-y limb FRA data.

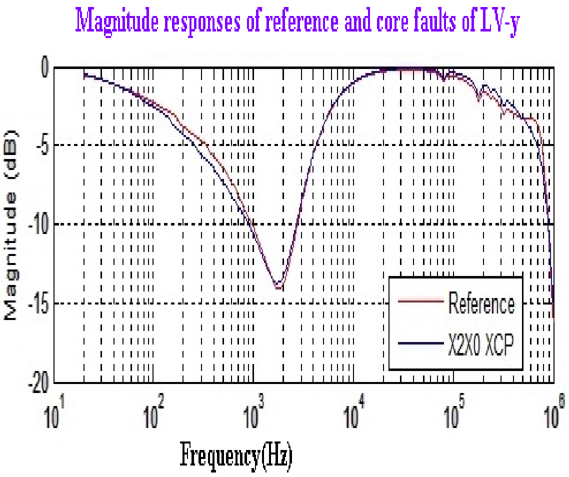
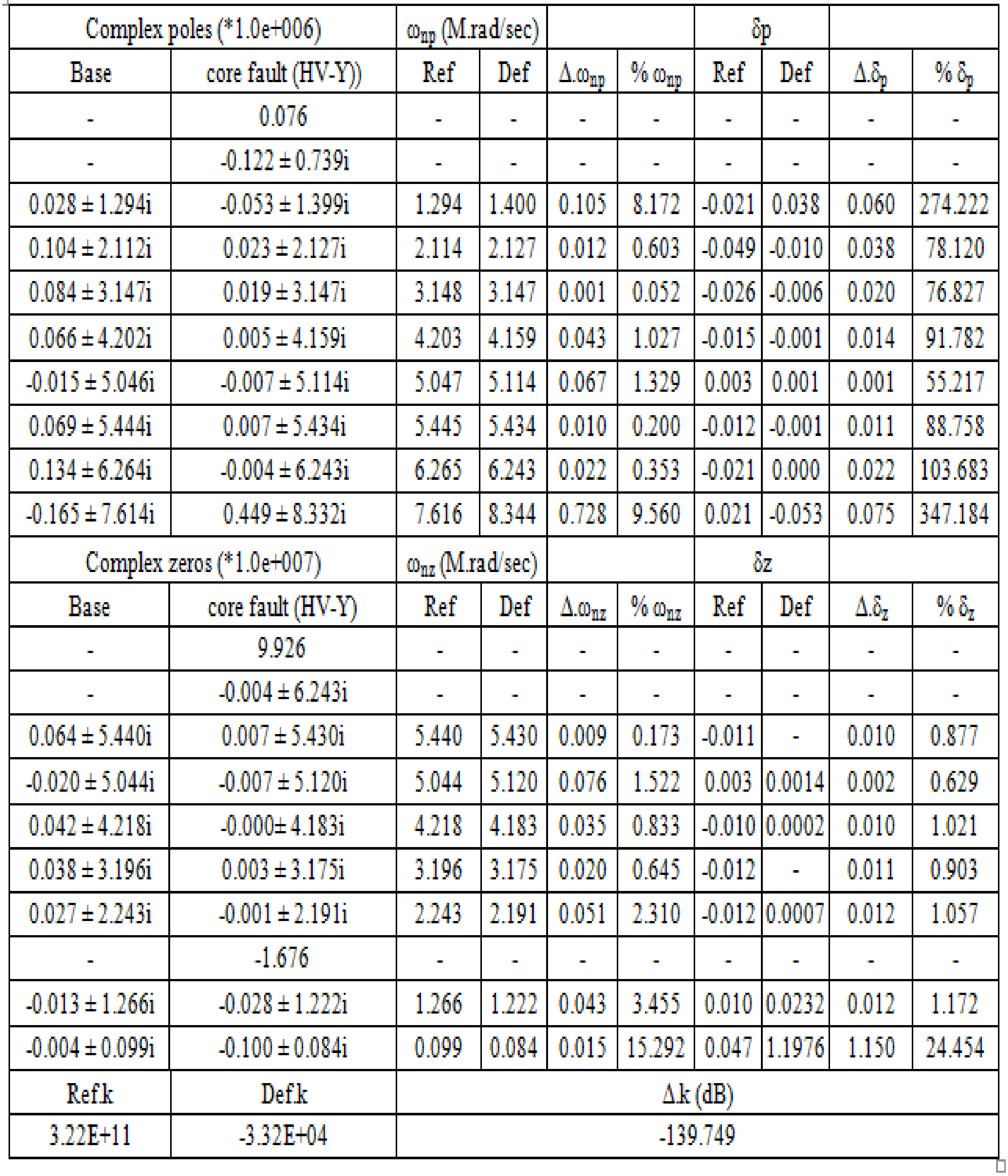


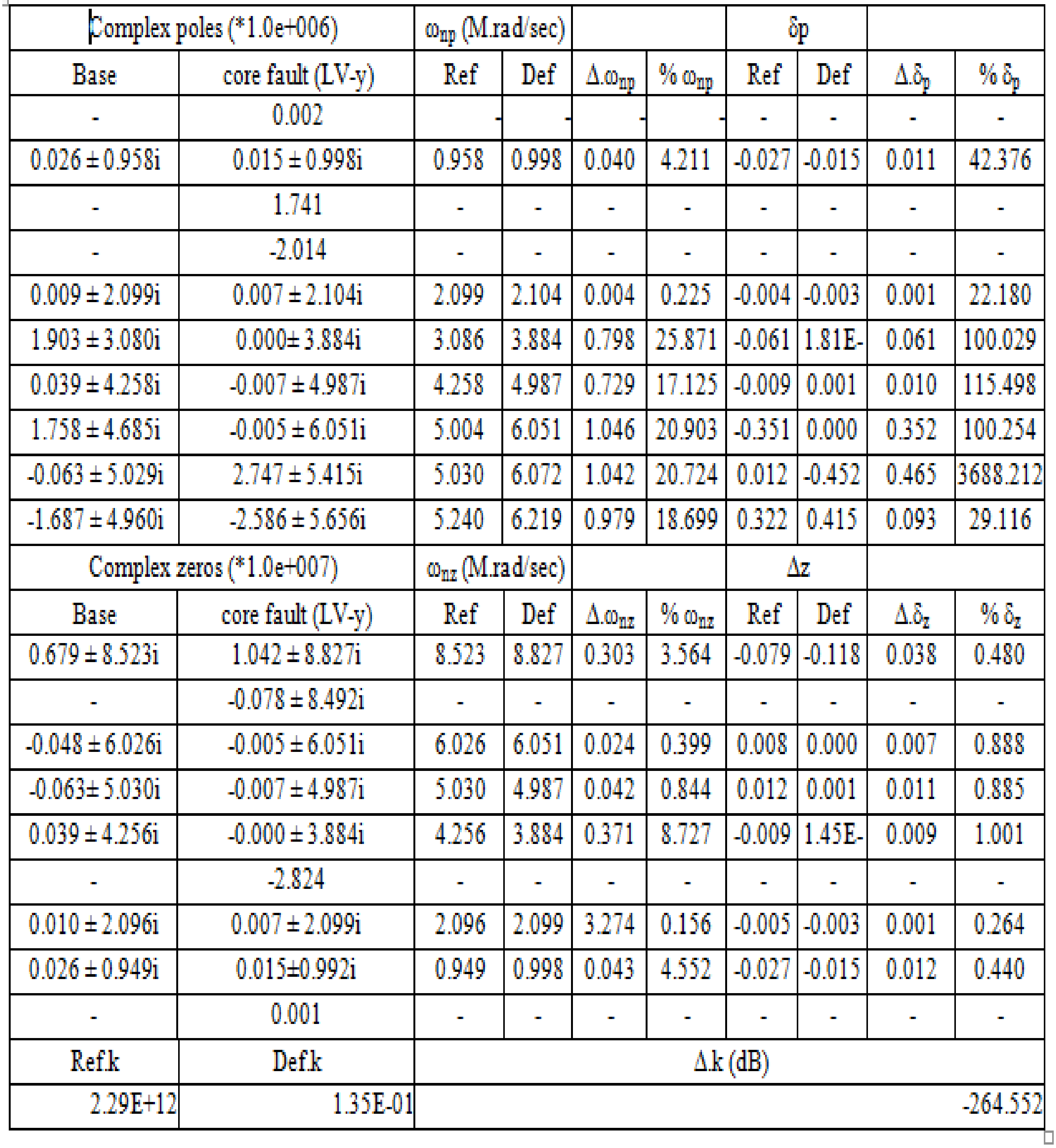
Figure 7. Magnitude responses of reference and core faults of LV-y.

TABLE I. TRANSFER FUNCTION PARAMETERS FOR CORE FAULT HV-Y LIMB OF TRANSFORMER



| Complex poles (*1.0e+006) | | $\omega_{np}$ (M.rad/sec) | | | | δp | | | |
|---|---|---|---|---|---|---|---|---|---|
| Base | core fault (HV-Y)) | Ref | Def | $\Delta.\omega_{np}$ | % $\omega_{np}$ | Ref | Def | $\Delta.\delta_p$ | % $\delta_p$ |
| - | 0.076 | - | - | - | - | - | - | - | - |
| - | -0.122 ± 0.739i | - | - | - | - | - | - | - | - |
| 0.028 ± 1.294i | -0.053 ± 1.399i | 1.294 | 1.400 | 0.105 | 8.172 | -0.021 | 0.038 | 0.060 | 274.222 |
| 0.104 ± 2.112i | 0.023 ± 2.127i | 2.114 | 2.127 | 0.012 | 0.603 | -0.049 | -0.010 | 0.038 | 78.120 |
| 0.084 ± 3.147i | 0.019 ± 3.147i | 3.148 | 3.147 | 0.001 | 0.052 | -0.026 | -0.006 | 0.020 | 76.827 |
| 0.066 ± 4.202i | 0.005 ± 4.159i | 4.203 | 4.159 | 0.043 | 1.027 | -0.015 | -0.001 | 0.014 | 91.782 |
| -0.015 ± 5.046i | -0.007 ± 5.114i | 5.047 | 5.114 | 0.067 | 1.329 | 0.003 | 0.001 | 0.001 | 55.217 |
| 0.069 ± 5.444i | 0.007 ± 5.434i | 5.445 | 5.434 | 0.010 | 0.200 | -0.012 | -0.001 | 0.011 | 88.758 |
| 0.134 ± 6.264i | -0.004 ± 6.243i | 6.265 | 6.243 | 0.022 | 0.353 | -0.021 | 0.000 | 0.022 | 103.683 |
| -0.165 ± 7.614i | 0.449 ± 8.332i | 7.616 | 8.344 | 0.728 | 9.560 | 0.021 | -0.053 | 0.075 | 347.184 |
| Complex zeros (*1.0e+007) | | $\omega_{nz}$ (M.rad/sec) | | | | δz | | | |
| Base | core fault (HV-Y) | Ref | Def | $\Delta.\omega_{nz}$ | % $\omega_{nz}$ | Ref | Def | $\Delta.\delta_z$ | % $\delta_z$ |
| - | 9.926 | - | - | - | - | - | - | - | - |
| - | -0.004 ± 6.243i | - | - | - | - | - | - | - | - |
| 0.064 ± 5.440i | 0.007 ± 5.430i | 5.440 | 5.430 | 0.009 | 0.173 | -0.011 | - | 0.010 | 0.877 |
| -0.020 ± 5.044i | -0.007 ± 5.120i | 5.044 | 5.120 | 0.076 | 1.522 | 0.003 | 0.0014 | 0.002 | 0.629 |
| 0.042 ± 4.218i | -0.000± 4.183i | 4.218 | 4.183 | 0.035 | 0.833 | -0.010 | 0.0002 | 0.010 | 1.021 |
| 0.038 ± 3.196i | 0.003 ± 3.175i | 3.196 | 3.175 | 0.020 | 0.645 | -0.012 | - | 0.011 | 0.903 |
| 0.027 ± 2.243i | -0.001 ± 2.191i | 2.243 | 2.191 | 0.051 | 2.310 | -0.012 | 0.0007 | 0.012 | 1.057 |
| - | -1.676 | - | - | - | - | - | - | - | - |
| -0.013 ± 1.266i | -0.028 ± 1.222i | 1.266 | 1.222 | 0.043 | 3.455 | 0.010 | 0.0232 | 0.012 | 1.172 |
| -0.004 ± 0.099i | -0.100 ± 0.084i | 0.099 | 0.084 | 0.015 | 15.292 | 0.047 | 1.1976 | 1.150 | 24.454 |
| Ref.k | Def.k | Δk (dB) | | | | | | | |
| 3.22E+11 | -3.32E+04 | -139.749 | | | | | | | |

TABLE II. TRANSFER FUNCTION PARAMETERS FOR CORE FAULT LV-Y LIMB OF TRANSFORMER.



| Complex poles (*1.0e+006) | | $\omega_{np}$ (M.rad/sec) | | | | $\delta p$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| Base | core fault (LV-y) | Ref | Def | $\Delta\omega_{np}$ | % $\omega_{np}$ | Ref | Def | $\Delta\delta_p$ | % $\delta_p$ |
| - | 0.002 | - | - | - | - | - | - | - | - |
| 0.026 ± 0.958i | 0.015 ± 0.998i | 0.958 | 0.998 | 0.040 | 4.211 | -0.027 | -0.015 | 0.011 | 42.376 |
| - | 1.741 | - | - | - | - | - | - | - | - |
| - | -2.014 | - | - | - | - | - | - | - | - |
| 0.009 ± 2.099i | 0.007 ± 2.104i | 2.099 | 2.104 | 0.004 | 0.225 | -0.004 | -0.003 | 0.001 | 22.180 |
| 1.903 ± 3.080i | 0.000± 3.884i | 3.086 | 3.884 | 0.798 | 25.871 | -0.061 | 1.81E- | 0.061 | 100.029 |
| 0.039 ± 4.258i | -0.007 ± 4.987i | 4.258 | 4.987 | 0.729 | 17.125 | -0.009 | 0.001 | 0.010 | 115.498 |
| 1.758 ± 4.685i | -0.005 ± 6.051i | 5.004 | 6.051 | 1.046 | 20.903 | -0.351 | 0.000 | 0.352 | 100.254 |
| -0.063 ± 5.029i | 2.747 ± 5.415i | 5.030 | 6.072 | 1.042 | 20.724 | 0.012 | -0.452 | 0.465 | 3688.212 |
| -1.687 ± 4.960i | -2.586 ± 5.656i | 5.240 | 6.219 | 0.979 | 18.699 | 0.322 | 0.415 | 0.093 | 29.116 |
| Complex zeros (*1.0e+007) | | $\omega_{nz}$ (M.rad/sec) | | | | $\Delta z$ | | | |
| Base | core fault (LV-y) | Ref | Def | $\Delta\omega_{nz}$ | % $\omega_{nz}$ | Ref | Def | $\Delta\delta_z$ | % $\delta_z$ |
| 0.679 ± 8.523i | 1.042 ± 8.827i | 8.523 | 8.827 | 0.303 | 3.564 | -0.079 | -0.118 | 0.038 | 0.480 |
| - | -0.078 ± 8.492i | - | - | - | - | - | - | - | - |
| -0.048 ± 6.026i | -0.005 ± 6.051i | 6.026 | 6.051 | 0.024 | 0.399 | 0.008 | 0.000 | 0.007 | 0.888 |
| -0.063± 5.030i | -0.007 ± 4.987i | 5.030 | 4.987 | 0.042 | 0.844 | 0.012 | 0.001 | 0.011 | 0.885 |
| 0.039 ± 4.256i | -0.000 ± 3.884i | 4.256 | 3.884 | 0.371 | 8.727 | -0.009 | 1.45E- | 0.009 | 1.001 |
| - | -2.824 | - | - | - | - | - | - | - | - |
| 0.010 ± 2.096i | 0.007 ± 2.099i | 2.096 | 2.099 | 3.274 | 0.156 | -0.005 | -0.003 | 0.001 | 0.264 |
| 0.026 ± 0.949i | 0.015±0.992i | 0.949 | 0.998 | 0.043 | 4.552 | -0.027 | -0.015 | 0.012 | 0.440 |
| - | 0.001 | - | - | - | - | - | - | - | - |
| Ref k | Def k | $\Delta$k (dB) | | | | | | | |
| 2.29E+12 | 1.35E-01 | -264.552 | | | | | | | |

It was observed that from Table II three new real poles at 0.002M rad/sec, 1.74M rad/sec, -2.01M rad/sec respectively and two real zeros at -2.82M rad/sec, 0.001M rad/sec, one complex pair of zeros at 8.49M rad/sec is created. Two real zeros, one complex pair of zeros and poles are eliminated. Major shift occurs at 7.61M rad/sec to in poles and at 0.09M rad/sec in zeros. Among the poles, highest shift is about 25.87% at 3.08M rad/sec, whereas in zeros highest shift is about 8.72% at 4.25M rad/sec.

However, large shift in natural frequency for poles of the TF of LV-y response is observed throughout except at 3M rad/sec. Here also, major change in damping factor is observed for all poles only.

For core faults, LV-y response of pole and zero locations have more influenced than that of HV-Y response. For LV-y response, larger change in gain was observed as compared HV-Y response.

## V. CONCLUSION

The transfer function and its characterizing parameters were computed for core faults using real rational polynomial technique.

Effectiveness of these parameters for detection of transformer core faults was studied. The inferences drawn from the distinguishing changes in the transfer function parameters for detection and location of core faults are listed below:

1. For core faults, Behavior changes in transfer function characterizing parameters for HV-Y less shift in frequency locations of both poles and zeros was observed.
2. For LV-y response of pole locations have more influenced than that of HV-Y response.

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