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Analyzing Transformer Winding Movements by Using Real-Rational Polynomial Function Model from FRA Data

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***Abstract*— The paper presents the results of the experimental investigation carried out on a transformer to obtain frequency response data under inter-turn deformations. These deformations 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 winding inter-turn deformations.**

Keywords: Frequency Response Analysis; Real-rational polynomial; Transfer Function; Winding deformations.

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 inter-turn deformation 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 winding for inter-turn deformations.

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.

Figure 1. A view of test specimen along with SFRA

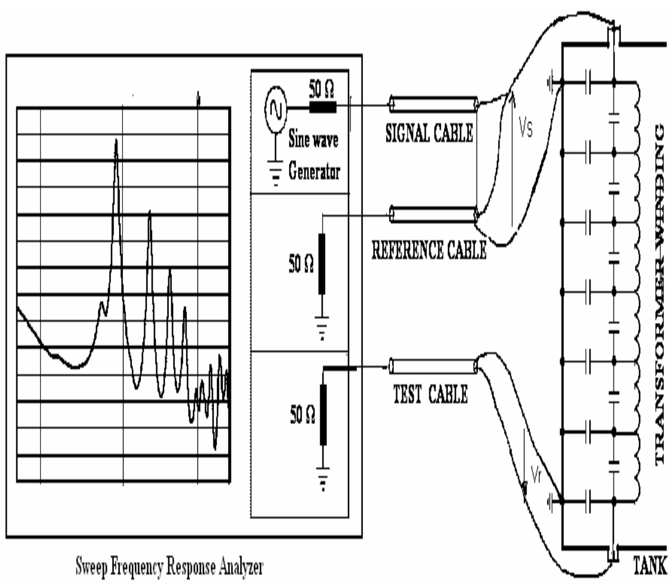

Figure 2. Schematic of the experimental set up for SFRA measurements.

Some 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 listed below [7].

End-to-end (open) measurement

End-to-end (short) measurement

A. 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. Inter turn deformation was simulated Y phase (middle limb) of HV winding and denoted as HV-Y and LV winding and denoted as LV-y for this measurement.

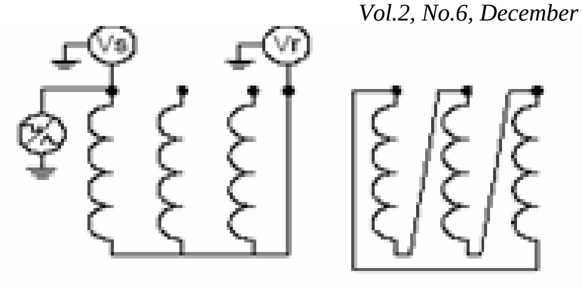

Figure 3. End-to-end (open) measurements.

B. End-to-end (open) measurement:

In end-to-end (short-circuit) 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, but with a winding on the same phase/or all secondary windings being short-circuited as shown in figure 4. Inter turn deformation was simulated Y phase (middle limb) of HV winding and denoted as HSCX-Y for this measurement.

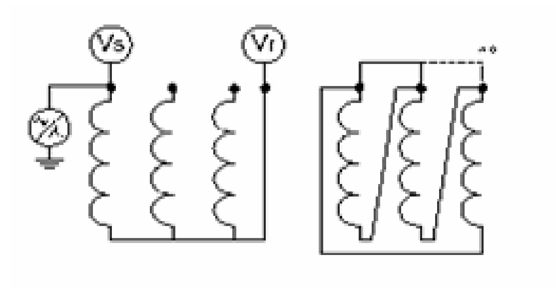

Figure 4. End-to-end (short-circuit) measurements

One turn short was simulated in Y phase (middle limb) of HV winding and denoted as HV-Y.

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 5 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. 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.

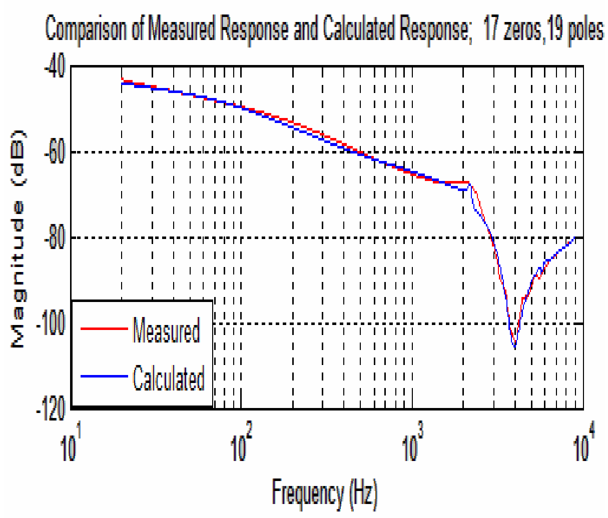

Figure 5. Measured and calculated magnitude response of transformer winding.

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.

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

$$\delta = \alpha / \omega_n \quad (3)$$

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

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 deformed TF 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.

One turn fault as shown in Figure 6 was created by shorting two adjacent turns of HV-Y phase limb to simulate inter-turn deformation, and here 2 types of measurements i.e. End-to-end (open) measurement (HV-Y,LV-y) and End-to-end (short) measurement(HSCX-Y) are considered for this inter-turn deformations, All measurement was done at top positions of the winding .

Figure 7 shows the measured magnitude responses of reference (base) and inter turn deformation top position fault from HV-Y limb FRA data. Table 1 gives the computed components of poles and zeros for transfer function of reference (base) and inter turn deformation top position fault from HV-Y limb FRA data.

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Figure 6. A view of test specimen with inter turn deformation at top position of HV-Y limb

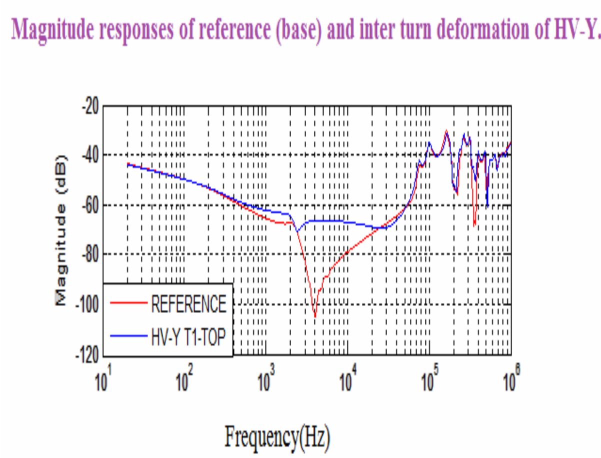

Figure 7. Magnitude responses of reference and inter-turn deformation faults of HV-Y.

TABLE I. : TRANSFER FUNCTION PARAMETERS FOR INTER TURN DEFORMATION FAULT AT TOP POSITION OF HV-Y LIMB OF TRANSFORMER.

Complex poles (*1.0e+006)		ω_{np}				δp			
Base	Inter turn deformation (top, HV-Y)	Ref	Def	$\Delta.\omega_{np}$	% ω_{np}	Ref	Def	$\Delta.\delta_p$	% δ_p
0.13±6.26i	-0.17±6.27i	6.26	6.27	0.009	0.15	-0.021	0.0274	0.049	2.27
0.064±5.44i	-0.042±5.48i	5.44	5.48	0.042	0.78	-0.011	0.0077	0.019	1.65
-0.020±5.04i	0.017±5.16i	5.04	5.16	0.122	2.41	0.0039	-0.0033	0.007	1.84
0.042±4.21i	-0.034±4.27i	4.21	4.27	0.054	1.28	-0.010	0.0080	0.018	1.79
0.038±3.19i	-0.028±3.27i	3.19	3.27	0.083	2.60	-0.012	0.0085	0.020	1.70
0.027±2.24i	-0.082±2.38i	2.24	2.38	0.137	6.11	-0.012	0.0347	0.047	3.84
-0.013±1.26i	0.043±1.54i	1.26	1.54	0.275	21.73	0.0106	-0.0281	0.038	3.62
-	0.134±0.63i	-	-	-	-	-	-	-	-
-	-0.0002	-	-	-	-	-	-	-	-
Complex zeros (*1.0e+007)		ω_{nz}				Δz			
Base	Inter turn deformation (top, HV-Y)	Ref	Def	$\Delta.\omega_{nz}$	% ω_{nz}	Ref	Def	$\Delta.\delta_z$	% δ_z
-	-0.008	-	-	-	-	-	-	-	-
-	0.094	-	-	-	-	-	-	-	-
0.0284± 1.29i	0.031 ± 1.59i	1.29	1.59	0.30	23.28	-0.021	-0.0200	0.002	8.84
0.104 ± 2.11i	-0.091 ± 2.28i	2.11	2.28	0.16	7.94	-0.049	0.0395	0.089	179.69
0.084 ± 3.14i	-0.033 ± 3.21i	3.14	3.21	0.07	2.22	-0.026	0.0103	0.037	138.68
-	-3.956	-	-	-	-	-	-	-	-
-	-0.048	-	-	-	-	-	-	-	-
-0.015± 5.04i	0.013± 5.16i	5.04	5.16	0.11	2.35	0.0031	-0.0025	0.005	181.12
0.069± 5.44i	-0.047± 5.48i	5.44	5.48	0.042	0.78	-0.012	0.0087	0.021	168.45
0.134± 6.26i	-0.16± 6.27i	6.26	6.27	0.01	0.16	-0.021	0.0269	0.048	225.76
-0.165± 7.61i	0.46± 7.37i	7.61	7.39	0.22	2.94	0.0217	-0.0629	0.084	388.80
Ref.k	Def.k	Δ.k (dB)							
9.96E+11	5.679E+11	-4.88035							

It is observed that from Table 1, two new real poles at 8k rad/sec, 3.95M rad/sec respectively and two complex pair of poles at 0.8M rad/sec, 4.42M rad/sec respectively and one real zero at 0.2k rad/sec and one complex pair of zeros 0.63M rad/sec are created. One real pole and zero, two complex pair of poles and one complex pair of zeros are eliminated. Major shift occurs at 1.26M rad/sec to 2.24M rad/sec in both poles and zeros. Among the poles, highest shift is about 23.28% at 1.29M rad/sec, whereas in zeros highest shift is about 21.73% at 1.26M rad/sec.

It can be seen that for Lower frequency (<10 kHz) a few poles and zero locations are added /deleted. At Medium frequency (10kHz-200kHz) a few poles and zeros have change more than 20%. At Higher frequency (>200 kHz) both poles and zeros have no significant change/influence. Damping coefficients beyond 200 kHz of zero locations have large change (130%) whereas the poles have insignificant change (5%). The gain has negligible change (about ± 5dB) for inter turn deformation fault.

Figure 8 shows the measured magnitude responses of reference (base) and inter turn deformation top position fault from LV-y limb FRA data. Table 2 gives the computed components of poles and zeros for transfer function of reference (base) and inters turn deformation top position fault from LV-y limb FRA data.

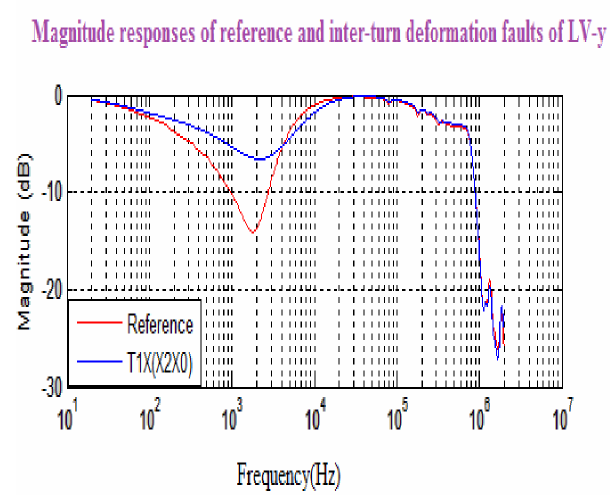

Figure 8. Magnitude responses of reference and inter-turn deformation faults of LV-y.

TABLE II. TRANSFER FUNCTION PARAMETERS FOR INTER TURN DEFORMATION FAULT AT TOP POSITION OF LV-Y LIMB OF TRANSFORMER

Complex poles (*1.0e+006)		ω_{np} (M.rad/sec)				δp			
Base	Inter turn deformation (top. LV-y)	Ref	Def	$\Delta.\omega_{np}$	% ω_{np}	Ref	Def	$\Delta.\delta_p$	% δ_p
	0.0006 ± 0.211i	-	-	-	-	-	-	-	-
	-1.053	-	-	-	-	-	-	-	-
1.537 ± 4.271i	-0.160± 3.244i	4.539	3.248	1.290	28.434	1	-0.338	0.049	4.943
-1.472 ± 4.551i	1.178 ± 4.629i	4.783	4.777	0.005	0.124	-0.317	0.307	-0.246	77.652
0.084 ± 6.128i	-0.806± 5.169i	6.128	5.231	0.897	14.639	0.293	-0.013	0.154	52.460
-0.019 ± 8.222i	0.207 ± 8.423i	8.222	8.426	0.204	2.485	0.083	0.002	-0.024	29.520
-0.024 ± 9.181i	-0.442± 9.812i	9.181	9.822	0.640	6.975	-0.076	0.002	0.045	59.256
0.657 ± 11.562i	-0.595 ± 11.547i	11.581	11.562	0.019	0.164	-0.005	-0.056	0.051	968.433
-0.668 ± 11.601i	0.544± 11.575i	11.620	11.587	0.032	0.282	-0.057	0.057	-0.047	81.285
Complex zeros (*1.0e+007)		ω_{nz} (M.rad/sec)				δz			
Base	Inter turn deformation (top. LV-y))	Ref	Def	$\Delta.\omega_{nz}$	% ω_{nz}	Ref	Def	$\Delta.\delta_z$	% δ_z
-	-14.654	-	-	-	-	-	-	-	-
0.993 ± 11.434i	0.750 ± 11.485i	11.434	11.485	0.050	0.445	-0.086	-0.065	0.021	0.248
-0.940± 11.389i	-0.738± 11.408i	11.389	11.408	0.018	0.161	0.082	0.064	0.017	0.216
-	-0.416 ± 9.923i	-	-	-	-	-	-	-	-
-	0.319 ± 8.421i	-	-	-	-	-	-	-	-
-0.023 ± 9.145i	2.719± 6.225i	9.145	6.225	2.919	31.927	0.002	-0.436	0.439	172.771
-0.011 ± 8.100i	-1.325 ± 5.732i	8.100	5.732	2.368	29.235	0.001	0.231	0.229	159.707
0.058 ± 6.196i	-0.266± 3.271i	6.196	3.271	2.924	47.198	-0.009	0.081	0.090	9.567
-	0.062 ± 0.140i	-	-	-	-	-	-	-	-
Ref.k	Def.k	Δ.k (dB)							
0.000561	0.033867	35.61944							

It was observed that from Table.2 one new real pole at -1.05M rad/sec, and one complex pair of poles at 0.21M rad/sec and one real zero at -14.658M rad/sec, and three complex pair of zeros at 9.92M rad/sec, 0.14M rad/sec and 8.42M rad/sec respectively is created. Three real poles and zeros, two complex pair of zeros are eliminated. Major shift occurs at 4.53M rad/sec in poles and at 6.19M rad/sec in zeros. Among the poles, highest shift is about 28.43% at 4.53M rad/sec, whereas in zeros highest shift is about 47.19% at 6.19M rad/sec.

It can be seen that for Lower frequency (<10 kHz) a few poles locations are added /deleted, and zeros locations are absent below 1 MHz. In addition to that the change in gain has more as compare to the HV-Y response for inter turn deformation fault.

Figure 9 shows the measured magnitude responses of reference (base) and inter turn deformation top position fault from HSCX-Y limb FRA data. Table 3 gives the computed components of poles and zeros for transfer function of reference (base) and inter turn deformation top position fault from HSCX-Y limb FRA data.

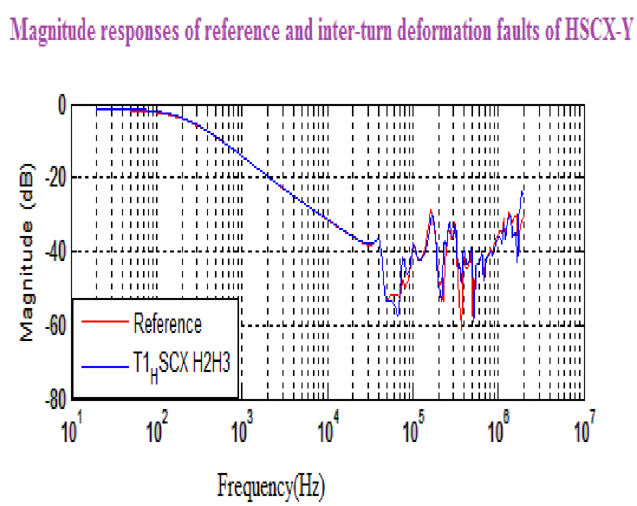

Figure 9. Magnitude responses of reference and inter-turn deformation faults of HSCX-Y.

TABLE III. TRANSFER FUNCTION PARAMETERS FOR INTER TURN DEFORMATION FAULT AT TOP POSITION OF HSCX-Y LIMB OF TRANSFORMER.

Complex poles (*1.0e+006)		ω_{np} (M.rad/sec)				δp			
Base	Inter turn deformation (top.HSCX-Y)	Ref	Def	$\Delta.\omega_{np}$	% ω_{np}	Ref	Def	$\Delta.\delta_p$	% δ_p
-	-0.0001	-	-	-	-	-	-	-	-
-	-0.572	-	-	-	-	-	-	-	-
0.178 ±2.986i	-0.052 ± 1.696i	2.991	1.696	1.294	43.274	-0.059	0.031	0.090	151.932
1.440 ± 6.097i	0.004 ± 4.146i	6.265	4.146	2.118	33.815	-0.229	-0.001	0.228	99.497
-0.240 ±7.817i	-0.088 ± 7.158i	7.821	7.159	0.662	8.466	0.030	0.012	0.018	59.743
-0.649 ± 7.840i	-0.971 ± 8.562i	7.866	8.617	0.750	9.542	0.082	0.112	0.030	36.653
-0.129 ±10.332i	0.802 ±8.590i	10.333	8.628	1.705	16.502	0.012	-0.093	0.105	840.289
0.130 ± 10.756i	-0.004 ± 10.645i	10.757	10.645	0.111	1.040	-0.012	0.0004	0.012	103.777
-0.215 ± 11.849i	-0.816 ± 12.076i	11.851	12.104	0.252	2.133	0.018	0.067	0.049	271.902
-0.495 ± 15.448i	0.825 ± 12.099i	15.456	12.127	3.329	21.540	0.032	-0.068	0.100	312.600
-	0.118 ± 12.499i	-	-	--	-	-	-	-	-
Complex zeros (*1.0e+007)		ω_{nz} (M.rad/sec)				δz			
Base	Inter turn deformation (top.HSCX-Y)	Ref	Def	$\Delta.\omega_{nz}$	% ω_{nz}	Ref	Def	$\Delta.\delta_z$	% δ_z
-	-31.708	-	-	-	-	-	-	--	-
0.060 ± 10.797i	0.134 ± 12.484i	10.797	12.484	16.871	15.624	-0.005	-0.010	0.005	0.912
-	-7.060	-	-	-	-	-	-	-	-
-0.149 ± 10.423i	-1.682± 10.022i	10.423	10.022	0.401	3.848	0.014	0.167	0.153	10.713
-1.422 ± 7.837i	-0.002 ± 10.592i	7.837	10.592	2.754	35.150	0.181	0.0002	0.181	0.998
-0.086 ± 7.762i	1.230 ± 9.365i	7.762	9.365	1.603	20.650	0.011	-0.131	0.142	12.812
1.391 ± 5.206i	-0.072 ± 7.303i	5.206	7.303	2.097	40.291	-0.267	0.009	0.277	1.037
0.005 ± 2.978i	-0.027 ± 4.039i	2.978	4.039	1.061	35.639	-0.001	0.006	0.008	4.562
-0.502 ± 0.996i	-0.002± 1.564i	0.996	1.564	0.567	57.012	0.504	0.001	0.502	0.996
	-0.004	-	-	-	-	--	-	-	-
Ref.k	Def.k	Δ.k (dB)							
2.38E+12	9.90E+17	112.3908							

It is observed that from Table 3 two new real poles at -0.1k rad/sec, -0.572M rad/sec respectively and one complex pair of poles at 12.4 M rad/sec and three real zeros at -31.708M rad/sec, -7.060 M rad/sec, and -0.004M rad/sec respectively is created. One real pole and zero, one complex pair of poles and one complex pair of zeros are eliminated. Major shift occurs at 2.99M rad/sec in poles and at 0.99M rad/sec in zeros. Among the poles, highest shift is about 43.27% at 2.99M rad/sec, whereas in zeros highest shift is about 57.07% at 0.99M rad/sec.

It was observed that lower frequency of both poles and zeros location are not changed. Medium to 1MHz frequency of both poles and zeros locations are similar behavior was observed as same as the HV-Y response.

V. Conclusion

The transfer function and its characterizing parameters were computed for inter turn deformation using real rational polynomial technique. Effectiveness of these parameters for detection of transformer winding inter-turn deformation faults was studied. The inferences drawn from the distinguishing changes in the transfer function parameters for detection and location of inter-turn deformation faults are listed below:

- HV-Y, at lower frequency (<10 kHz) a few poles and zero locations are added /deleted. At Medium frequency (10kHz-200kHz) a few poles and zeros have change more than 20%. At Higher frequency (>200 kHz) both poles and zeros have no significant change/influence. Damping coefficients beyond 200 kHz of zero locations have large change (130%) whereas the poles have insignificant change (5%). The gain has negligible change (about ± 5dB) for inter turn deformation fault.
- For LV-Y, at Lower frequency (<10 kHz), a few poles locations are added /deleted. Zeros locations are absent below 1 MHz In addition to that the change in gain has more as compare to the HV-Y response for inter turn deformation fault.
- For HSCX-Y, at lower frequency of both poles and zeros location are not changed. Medium to 1MHz frequency of both poles and zeros locations are similar behavior was observed as same as the HV-Y response.
- No other specific trends in TF characterizing parameters that could suggest the possibility of indentifying the position of the deformations is observed.

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