International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075, Volume-1 Issue-5, October 2012

Interpreting Transformer Winding Axial Displacements using Transfer Function Parameters

K. Sahitya Yadav, M. Prameela, K. Sumanth, G. Radhakrishna Murthy, Pradeep M. Nirgude

Abstract— The paper presents the results of the experimental investigation carried out on a transformer to obtain frequency response data under axial displacements. These displacements were physically simulated to study and identify the various parameters that influence the frequency responses. Transfer Function using real rational polynomial technique 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 axial displacements.

Index Terms— Frequency Response Analysis, Real rational polynomial technique, Transfer Function, Transformer winding axial displacement.

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 deformations and displacements of the windings. These are caused by enormous electromagnetic stresses experienced by transformer due to large short circuit currents. Once a winding is displaced, 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.

Manuscript received on October, 2012.

Ms. K. Sahitya Yadav, EEE Department, Sreenidhi Institute of Science & Technology, Ghatkesar, Hyderabad, Andhra Pradesh, India.
Mrs. M. Prameela, EEE Department, Vignan University, Guntur, Andhra Pradesh, India.
Dr.K. Sumanth, EEE Department, Sreenidhi Institute of Science & Technology, Ghatkesar, Hyderabad, Andhra Pradesh, India.
Dr. G. Radhakrishna Murthy, EEE Department, Vignan University, Guntur, Andhra Pradesh, India.
Dr. Pradeep M. Nirgude, UHV Research Laboratory, Central Power Research Institute, Hyderabad, Andhra Pradesh, India.

Deformation/displacement 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 axial displacement simulated on a transformer core and coil assembly. Mathematical Transfer Function (TF) using real rational polynomial technique 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 axial displacements.

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. 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.

Figure 2 shows the schematic of the SFRA measurements on transformers. 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 [7]. In this test configuration, the input signal is applied to one end of the

Fig. 1: A view of test specimen.

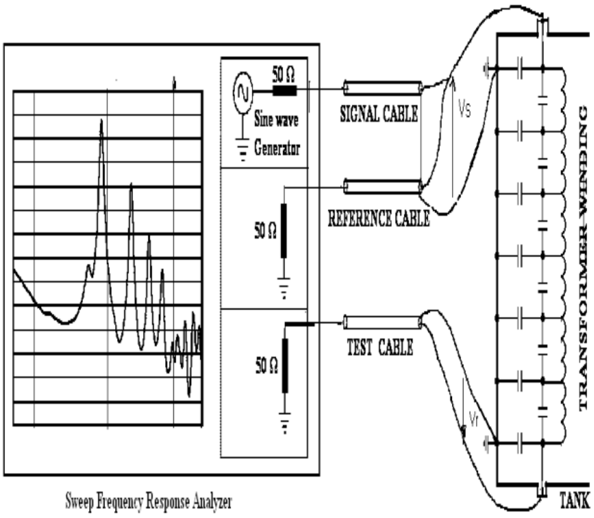

Fig. 2: Schematic of the experimental set up for SFRA measurements.

winding and the transmitted signal at the other end of the same winding is measured. All other terminals of the transformer are left open. Axial displacement was simulated Y phase (middle limb) of HV winding and denoted as HV-Y and LV winding and denoted as LV-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 3 shows the measured frequency response and calculated frequency response using real rational polynomial

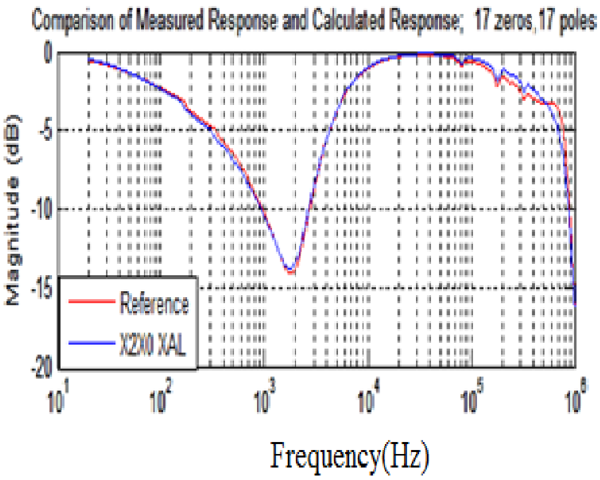

Fig.3: Measured and calculated magnitude responses of transformer winding.

Technique for magnitude response plot of a transformer winding wherein the best-fitted function was achieved with 17 zeros and 17 poles. It can be observed from the figure that, calculated transfer function is closely matching with measured response. Similarly, the TF were computed for axial displacement winding faults considered in this study.

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.

Axial displacement type effects are studied by changing axial height of winding. The mild steel clamping ring placed at the top end of winding between the perm wood ring and top clamping structure and supported by insulating stiffeners to give the axial mechanical strength. The clamping ring is earthed. Change in axial clearances for HV & LV winding was simulated by removing the earth connection to the clamping ring as shown in Figure 4. This will result in a small reduction in ground capacitance Figure 5 shows the measured magnitude responses of HV-Y limb winding with axial displacement faults. Table I gives the computed components of poles and zeros for transfer function of reference (base) and axial displacement fault for HV-Y limb FRA data. Figure 6&7 shows the measured magnitude responses of LV-y, LV-r limb winding with axial displacement fault.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Fig. 4: A view of test specimen with axial displacement.

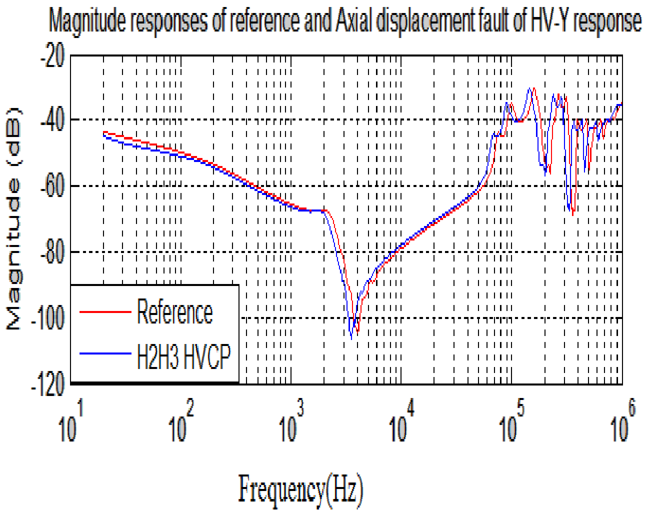

Fig. 5: Magnitude responses of reference and Axial displacement fault of HV-Y response.

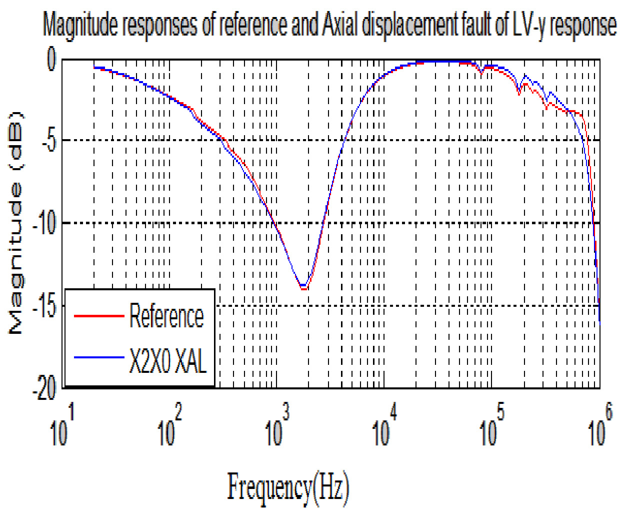

Fig. 6: Magnitude responses of reference and Axial displacement fault of LV-y response.

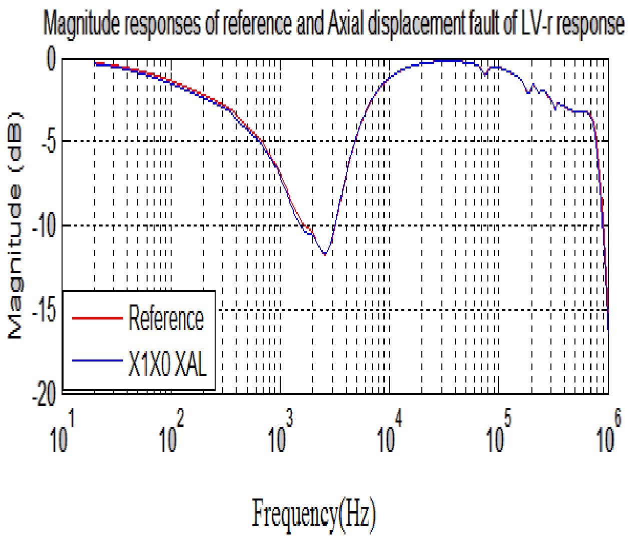

Fig. 7: Magnitude responses of reference and Axial displacement fault of LV-r response.

It is observed from Table I that, one new real pole at 0.054M rad/sec and one complex pair of poles at 0.77M rad/sec and three real zeros at 4.19Mrad/sec, 0.217Mrad/sec, and 0.098Mrad/sec respectively are created. One real pole and zero, one complex pair of poles and two complex pair of zeros are eliminated. Major shift occurs at 1.24M rad/sec to 1.29M rad/sec in both poles and zeros. Among the poles, highest shift is about 20.22% at 1.29M rad/sec, whereas in zeros highest shift is about 4.84% at 1.26M rad/sec. It can be seen that, for frequencies between 200 kHz to 500 kHz, poles and zeros locations have maximum shift. Damping coefficient change at the natural frequency of only the pole locations have major shift. The HV-Y response has maximum change in absolute value of gain.

Table I: Transfer function parameters for axial displacement fault of HV-Y response

Complex poles (*1.0e±006)		ω_{np}				δp			
Base	Axial displacement (HV-Y)	Ref	Def	$\Delta.\omega_{np}$	% ω_{np}	Ref	Def	$\Delta.\delta_p$	% δ_p
-	0.054	-	-	-	-	-	-	-	-
-	-0.102 ± 0.779i	-	-	-	-	-	-	-	-
0.028 ± 1.294i	-0.062 ± 1.555i	1.29	1.55	0.261	20.22	-0.02	0.04	0.062	283.84
0.104 ± 2.112i	-0.048 ± 2.380i	2.11	2.38	0.266	12.58	-0.04	0.02	0.069	140.96
0.084 ± 3.147i	-0.058 ± 3.379i	3.14	3.37	0.230	7.326	-0.02	0.01	0.044	165.19
0.066 ± 4.202i	-0.079 ± 4.315i	4.20	0.43	0.113	2.691	-0.01	0.01	0.034	215.82
-0.015 ± 5.046i	0.014 ± 5.007i	5.04	5.00	0.039	0.778	0.00	-0.00	0.006	194.42
0.069 ± 5.444i	0.013 ± 6.008i	5.44	6.00	0.562	10.33	-0.01	-0.00	0.010	81.997
0.134 ± 6.264i	1.210 ± 6.201i	6.26	6.31	0.052	0.835	-0.02	-0.19	0.170	795.21
-0.165 ± 7.614i	-1.070 ± 6.227i	7.61	6.31	1.298	17.04	0.02	0.16	0.147	677.64
Complex zeros (*1.0e±007)		ω_{nz}				δz			
Base	Axial displacement (HV-Y)	Ref	Def	$\Delta.\omega_{nz}$	% ω_{nz}	Ref	Def	$\Delta.\delta_z$	% δ_z
0.135 ± 6.266i	0.013 ± 6.008i	6.26	6.008	0.25	4.118	-0.02	-0.00	0.019	0.891
-0.020 ± 5.044i	0.012 ± 5.007i	5.04	5.007	0.03	0.717	0.00	-0.00	0.006	1.647
-	-4.196	-	-	-	-	-	-	-	-
0.042 ± 4.218i	-0.091 ± 4.296i	4.21	4.296	0.07	1.856	-0.01	0.02	0.031	3.107
0.038 ± 3.196i	-0.071 ± 3.324i	3.96	3.324	0.12	3.998	-0.01	0.02	0.033	2.767
0.027 ± 2.243i	-0.034 ± 2.294i	2.24	2.294	0.05	2.246	-0.01	0.01	0.027	2.228
-0.013 ± 1.266i	-0.066 ± 1.327i	1.26	1.327	0.06	4.844	0.01	0.04	0.039	3.653
-	-0.217	-	-	-	-	-	-	-	-
-	-0.098	-	-	-	-	-	-	-	-
Ref.k	Def.k	Δ.k (dB)							
3.22E±11	2.68E±24	258.4089							

Table II: Transfer function parameters for axial displacement fault of LV-y response

Complex poles (*1.0e±006)		ω_{np}				δp			
Base	Axial displacement (LV-y)	Ref	Def	$\Delta.\omega_{np}$	% ω_{np}	Ref	Def	$\Delta.\delta_p$	% δ_p
-	0.002	-	-	-	-	-	-	-	-
0.026 ± 0.958i	0.019 ± 1.063i	0.958	1.06	0.105	10.97	-0.0	-0.0	0.008	31.819
-	1.546	-	-	-	-	-	-	-	-
-	-1.727	-	-	-	-	-	-	-	-
0.009 ± 2.099i	0.012 ± 2.166i	2.099	2.16	0.066	3.179	-0.0	-0.0	0.001	33.797
0.190 ± 3.080i	0.019 ± 4.010i	3.086	4.01	0.924	29.94	-0.0	-4.9	0.056	92.015
0.039 ± 4.258i	-0.006 ± 4.639i	4.258	4.63	0.381	8.955	-0.0	0.00	0.017	183.61
1.758 ± 4.685i	2.724 ± 4.820i	5.004	5.53	0.532	10.64	-0.3	-0.4	0.140	40.038
-0.063 ± 5.029i	-2.626 ± 5.170i	5.030	5.79	0.769	15.29	0.01	0.45	0.440	3491.6
-0.048 ± 6.026i	-0.011 ± 6.215i	6.027	6.21	0.188	3.125	0.00	0.00	0.006	76.723
Complex zeros (*1.0e±007)		ω_{nz}				δz			
Base	Axial displacement (LV-y)	Ref	Def	$\Delta.\omega_{nz}$	% ω_{nz}	Ref	Def	$\Delta.\delta_z$	% δ_z
0.679± 8.523i	2.606 ± 12.735i	8.52	12.73	4.21	49.40	-0.0	-0.2	0.124	1.566
-0.048 ± 6.026i	0.197 ± 7.985i	6.02	7.985	1.95	32.49	0.00	-0.0	0.032	4.067
-0.063 ± 5.030i	-0.011 ± 6.215i	5.03	6.215	1.18	23.55	0.01	0.00	0.010	0.852
0.039 ± 4.256i	-0.036 ± 4.639i	4.25	4.639	0.38	9.003	-0.0	0.00	0.017	1.847
0.191 ± 3.085i	0.019 ± 4.009i	3.08	4.009	0.92	29.93	-0.0	-0.0	0.057	0.920
-	-2.376	-	-	-	-	-	-	-	-
-	2.109	-	-	-	-	-	-	-	-
0.010 ± 2.096i	0.013 ± 2.161i	2.09	2.161	0.06	3.113	-0.0	-0.0	0.001	0.235
0.026 ± 0.949i	0.019 ± 1.053i	9.49	1.053	0.10	10.94	-0.0	-0.0	0.008	0.317
-	0.001	-	-	-	-	-	-	-	-
Ref.k	Def.k	Δ.k (dB)							
2.29E±12	5.31E-02	-272.685							

Table II gives the computed components of poles and zeros for transfer function of reference (base) and axial displacement LV-y limb FRA data. It can be observed that, three new real poles at 0.002 Mrad/sec, 1.5M rad/sec, 1.7M rad/sec respectively and three real zeros at 2.3M rad/sec, 2.1M rad/sec, 0.001 rad/sec respectively are created. Three real poles and zeros are eliminated. Major Shift occurs at 3.08M rad/sec in poles and 8.523 M rad/sec in zeros. Among the poles, highest shift is about 29.941% at 3.08M rad/sec, whereas in zeros highest shift is about 49.40% at 8.52M rad/sec.

It can be also be seen from Table II that, for pole certain locations between 500 kHz – 800 kHz frequencies and zero locations for frequencies above 800 kHz have maximum shift than at other frequencies. Damping coefficient change at the natural frequency of pole locations were major shift than zeros locations. The LV-y response has maximum change in absolute value of gain.

The clamping ring of the middle limb was only disconnected keeping the other two limbs rings connected to earth. It can be observed from Fig. 7 that, there is no change in the frequency responses of LV–r limb before and after the removal of clamping ring connection in Y limb. Similarly, all the computed parameters of the TF of LV-r limb do not show any deviation from their reference values.

It can be observed from Table I that, for HV-Y response, both the poles and zeros at certain locations for frequencies between 200 kHz-500 kHz of the faulty phase response are influenced However, it can be observed from table 2 that, for LV-y response, frequencies between 500 kHz-800 kHz of poles and above 800 kHz for zero locations of the faulty phase response are influenced.

It can also be observed from Table I and II that, the HV-Y response has maximum change in damping coefficient at throughout all poles location, whereas LV-y response has maximum change in damping coefficient at 5.03Mrad/sec poles location. In addition, HV-Y response gave maximum increment in gain and maximum reduction in gain for LV-y response gain.

V. CONCLUSION

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

1) Poles and zero at certain locations of both HV and LV winding transfer function are influenced (i.e. above 2% change) for frequencies above 200 kHz.
2) The damping coefficient of all pole locations above 200 kHz for both HV and LV winding TF only are highly influenced.
3) The damping coefficient of all zero locations for both HV and LV winding TF only are not influenced.
4) The maximum change in the absolute value of overall gain for HV and LV winding transfer function.

ACKNOWLEDGMENT

First Author, Second Author, Third Author and Fourth Author wish to thank the management of CPRI, India for permitting to carry out the research work.

REFERENCES

1. J. Lapworth and T.McGrail, “Transformer winding movement detection by frequency response analysis,” Proc. 66th Annual International Conference of Doble Clients- April, 1999, Boston, USA.
2. J.W. Kim, B. Park, S.C. Jeong, S.W. Kim, and P. Park, “Fault diagnosis of a power transformer using an improved frequency response analysis,” IEEE Trans. on Power Delivery, 20, (21), pp.169-178, Jan. 2005
3. Leibfred,T., and Feser, K.: “Monitoring of power transformers using the transfer function method”, IEEE Trans. on Power Delivery, Vol.14, No.4, pp. 1333-1341, October 1999.
4. Dick, E.P., and Erven, C.C.: ‘Transformer diagnostic testing by frequency response analysis’, IEEE Trans. on Power App. and Syst., Nov.-Dec.1978, PAS-97, (6), pp. 2144-2153
5. CIGRE SC12 Transformer Colloquium, Summary on behalf of Study Committee 12, Budapest, 14 -16 June 1999.
6. D.M. Sofian, Z.D. Wang, J.A.S.B. Jayasinghe, P.N.Jarman and S.A.Ryder, “Analysis and interpretation of Transformer FRA measurement Results using Transfer Function Estimation,” Proc. XIV ISH, Tsinghua University, Beijing, China, August 25-29, 2005.
7. CIGRE Working Group-A2.26 document on “Mechanical-Condition Assessment Of Transformer Windings Using Frequency Response Analysis (FRA)”, 2008.
8. Users Guide with MATLAB, The Mathworks, Inc, 2006.

AUTHORS PROFILE

Ms. K. Sahitya Yadav obtained her Bachelor of Technology(Electrical and Electronics Engineering) from Padmasri Dr. B V Raju institute of technology afflicted to JNT University, Hyderabad, Andrapradesh State, India in the year 2009. She is pursuing Master of Technology (Electrical Power Engineering), from Sreenidhi Institute of Science and Technology, Autonomous, Hyderabad, Andrapradesh State, India. She is doing her M.tech academic project at UHV Research Laboratory,
Central Power Research Institute, Hyderabad, India.. Her interest areas are Diagnostic & condition assessment of transformers, Electrical machines and control systems. She has two research publications in various National and International conferences and Journals.

Mrs. M. Prameela obtained her BE in Electrical Engineering from Sri Venkateswara University and M.Tech from the JNTU, Kakinada. She worked for about 17 years in different capacities in the IT sector and Department of Electrical Engineering at various reputed Engineering colleges in Andhra Pradesh. She is pursuing her Ph.D. program at Vignan University, Guntur, India. Her research interests include energy conservation, electric drives, IT applications in engineering and Diagnostic & Condition assessment of transformers. She has nine research publications in various National and International conferences and Journals.

Dr. G. Radhakrishna Murthy obtained his BE in Electrical Engineering from Andhra University, India in 1960 and his M.Tech and Ph.D from the Indian Institute of Technology, Kharagpur, India in 1971 and 1979 respectively. He worked for 38 years in different capacities in the Department of Electrical Engineering at JNT University, India. He is currently working as professor in Electrical Engineering at K.L.University, Vaddeswaram, Guntur District. His research interests include energy conservation and electric drives, development of Hybrid Power sources, application of Artificial intelligence and identification of faults in power equipment.

Dr. K. Sumanth has obtained his B.E.(Electrical Engineering) from Bangalore University, M.E.(Power Systems) from Anna University, Madras and Ph.D.(Electrical Engineering) from Jawaharlal Nehru Technological University, Hyderabad. He is presently working as Professor in Department of Electrical & Electronics Engineering and Dean (Industrial Consultancy Centre) at Sreenidhi Institute of Science and Technology, Hyderabad.

He has earlier worked with TATA Consulting Engineers (TCE) for more than one-and-half decades in Design Engineering Division and was also actively involved in Inspection & Expediting activities for various Electrical Equipment at manufacturers works. His areas of interest are Power System Voltage Stability, Demand Side Management techniques, Power evacuation system planning with respect to private sector participation, Available Transfer Capability of transmission system and Transformer Testing. He is an Associate member of Institution of Electronics & Telecommunication Engineers and a Member of IEEE.

Dr. Pradeep M. Nirgude obtained his B.E.(EE), M.E.(High Voltage) and Ph.D degrees in 1986, 1988 and 2006 from Bangalore Unviersity, Anna University and Osmania University respectively. He worked as lecturer for about 2 years before joining CPRI in 1989. He is presently working as Joint Director at UHV Research Laboratory, Central Power Research Institute, Hyderabad. His areas of interest

include High voltage testing & measurements, Insulation coordination, Air insulation studies, Optimization of transmission line tower- window clearances, Electric field Analysis of power equipments, Pollution performance of insulators/surge arrestors, Corona/RIV performance of transmission lines/equipments and Diagnostics & condition assessment of power transformers by Frequency Response Analysis**.** He has sixty five research publications in various National and International conferences and Journals.