Power Transformer Windings Partial Discharge Localization by Transfer Function

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Abstract—In this paper, the transfer function method is presented as a tool for detection the deformation of the transformer windings. In the first stage this deformation appears as a partial discharge in the interior part of the transformer insulations specifically and between windings.
The main objective of this study is to develop, and to create the mathematical models which help in the testing procedures and evaluating process of the transformer interior dielectric conditions. These developments and improvements of the partial discharge (PD) localization methods in the transformers enable to minimize the test time and to define the deformed part of the insulations with high accuracy. Correspondingly measuring, maintenance and repair time of the transformer. The measurements by the frequency response analyses used to define the transfer function for modeling the transformers and to obtain the correlation between its characteristics. Practically, the splitting techniques of the Transfer function into a sectional winding transfer function a long the windings has been approved to localize the defected origin.

Keywords—Winding deformations, Transfer function, Partial discharge localization, frequency response analyses.

I. Introduction

Normal operation, time aging, short circuit currents, or even forces during transport can cause mechanical deformation and displacement of transformer windings. These deformations cause defect that cause a behavior such as PD (hot spots) or fault source, in the interior of the transformer. The transfer function (TF) method can be used as a tool to detect this deformation. In order to evaluate the mechanical conditions, the correlation between the characteristics of transfer functions and possible damages must be defined.

For electric energy equipments mathematical modeling is one of the most important issues. The Power transformers are expensive components. The model is employed for simulating the performance of the transformer. The majority of them have been in service for many years under different environmental, electrical, and mechanical conditions. Power transformers are very expensive and form a high percentage of the investment of a power system. Extending transformer life as long as possible is not only economically valuable, but also prevents lost revenues when power outages occur [1],[2].

In the power engineering area, wide frequency range modeling of transformers and reactors by frequency domain external measurements is sometimes required for the study of electromagnetic transient. Besides, the Mathematical representation of such equipment is particularly important in insulation coordination of applications involving HV and EHV systems, where precise prediction of possible system overvoltages is essential to achieve an economical and reliable design [2].

The transformer general simple model (equivalent circuit) consist of a string of inductances tapped by their parallel capacitances to earth and shunted by their stray capacitances between windings [5] .In reality, every transformer has a unique, identical model which considered as the fingerprint of the transformer.

According to applications, purposes and analysis, models can be classified into different approaches:

- The model before building
- The model based on the manufacturing data (status)
- The model based on the operations conditions (after working and aging)

PD measurement is a powerful technique used to detect an incipient insulation fault in a power transformer. Research is being carried out to detect, locate and classify the type of PD. Techniques for the localization of PD sources are of major importance in on-site maintenance and repair [2],[4].

The PD is a major source of mechanical deformations such as: insulation failure which leads to defects in power transformers. Defects can be recognized by the measurement of the transfer function of the individual transformer coils such as turn short circuits or deformations. The PD caused the mechanical deformation of the dielectric isolation material surrounding the transformer windings and transformer bushing. The location of PD source is of crucial importance in both the maintenance and repair of a transformer.

PD measurement is still usually accomplished offline. There are already electrical procedures, which permit a detection of the source of PD beside the intensity of the PD. With the help of the determination of the transfer function, this can take place online or offline. By which the mechanical deformation of the coils (windings) and its insulation can be determined [3],[9],[11] The General main objective of this study is to develop and create the mathematical models of the transformer which help in the procedures of testing describing and evaluating the transformer dielectric conditions particularly, PD Localization modeling and measurements.

Most of the practical PD site location methods depend on time domain reflect, when a PD pulse occurs, it will travel through the test object (typically a power cable, switchgear or winding) and reflect at the end of the test object (a bushing or terminal).

A. *Use of the Transfer Function in PD Measurements:*

In general the transfer function (TF) is an approximation to the Fourier transformed impulse response $H(w)$. It is calculated as the quotient of an applied input signal $X(w)$ and its response $Y(w)$ in frequency domain according to:

$$TF(w) = \frac{Y(w)}{X(w)} \tag{1}$$

For this investigation $X(w)$, and $Y(w)$ have been determined by a Fourier transformation of an applied low-voltage impulse $x(t)$ and its response signal $y(t)$ (low-voltage impulse frequency response analysis) [2],[9],[11]. There is a redundancy between the magnitude and the phase of $TF(w)$ for minimal phase systems [6] . Therefore, only the magnitude $TF(w)$ is chosen for an experimental evaluation of TF results. The TF method is an approach for diagnosing changes in core-and-coil assemblies of power transformers by comparing a measured TF with a reference.
Frequency Response Analysis, generally known as FRA, is a powerful diagnostic test technique. FRA consists of measuring the impedance of transformer windings over a wide range of frequencies and comparing the results of these measurements to a reference set. Differences may indicate damage to the transformer, which can be investigated further using other techniques or by an internal examination.

Frequency dependencies of the winding admittance or TF forms are the basis of the FRA method (see Figure 1). The output of both the admittance and TFs contains a number of peaks occurring at the natural oscillation frequencies resulting from the serial and parallel resonance between capacities and winding inductance [6],[7],[13].

This method is based on the TF being usually proportional between current I that measured in a winding and a supply voltage U applied to another winding, calculated in the frequency domain according to:

$$TF(w) = \frac{I(w)}{U(w)} \tag{2}$$

The measurement result in equation (2), is the admittance of the winding $Y = Z^{-1} = \frac{I(w)}{U(w)}$. Therefore, measurement of the insulation resistance or the results of winding admittance can be used to detect this kind of PD and winding failure. Theoretically it should be less when PD accurse [12].

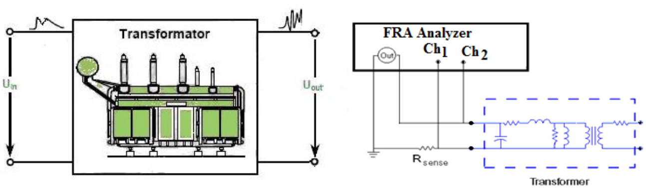

Fig. 1. :The general FRA measuring schematic diagram and its circuit.

FRA measurements can be considered as fingerprint of the transformer dielectric conditions. If any changes in the internal transformer dielectric caused for any reason, the measured rustles (curves) should be changed correspondingly.

B. Developing the Transfer Function Model for PD Localization

The frequency response of the transformer winding can be considered as multi-input multi-output,and in general can be simplified as [3],[4]:

$$y = Hu \tag{3}$$

where: u - the input complex vectors, y - the output complex vectors, H - the symmetrical or non symmetrical transfer matrix defined by a certain discrete observed frequencies m on the interval sω_k, where:

$$\omega_a \leq \omega_k \leq \omega_b \tag{4}$$

The matrices in equation (3), as should be suitable for any all mathematical operation that can be needed. These purposes can be achieved be means of diagonalization. In linear algebra, matrix diagonalization is the process of taking a square matrix and converting it into a special type of matrix so called diagonal matrix that shares the same fundamental properties of the underlying matrix. The diagonalization of matrices in equation (3) can be as:

$$u = T_u u_m, y = T_y y_m \tag{5}$$

Then equation 3 will be:

$$y_m = H_m u_m \tag{6}$$

The transformation matrices will be as:

$$H_m = T_y^{-1} H T_u \tag{7}$$

This should be identical and satisfied with the particular frequency ω_0. The diagonal elements of H_m in position μ evaluated for m discrete frequency values ω_k with a fixed transformation

$$H_\mu(j\omega_k) = [H_\mu(j\omega_k)]_\mu \tag{8}$$

where:

$$\omega_a \leq \omega_k \leq \omega_b$$
$$\mu = 1, ..., r$$
$$k = 1, ..., m$$

According to Soysal [2], the TF estimation can be determined as:

$$H_\mu(S) = \sum_i \frac{a_{\mu,i}}{s - \lambda_{\mu,i}} \tag{9}$$

where:

$$\mu = 1, ..., r, i = 1, ..., n_\mu$$

Generally the $a_{\mu,i}$ and $\lambda_{\mu,i}$ designated the strength and location of poles. And they may be real and complex numbers.

It was denoted that power transformers windings can be considered as multi-input multi-output system, which is linear and time invariant [3],[9]. PDs can be occurred in any place along the winding coils of the transformer which can be considered as input to the system as it shown in Fig. 1 , (Note that, the wards input and output are relevant). The place of PD depends on the insulation conditions and its break down degree.

The mathematical representation of the TF can be written as matrices:

$$[V] = [H_{ik}] \times [PD] \tag{10}$$

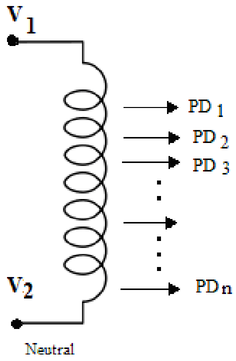

Fig. 2. :Illustration of the Winding PD

The H_{ik} is the sectional winding TF between the input k and out put i , specifically it can be written as:

$$[V] = \begin{bmatrix} H_{11} & H_{12} & & H_{1n} \\ H_{21} & H_{22} & & H_{2n} \end{bmatrix} \times [PD] \qquad (11)$$

where the matrices

$$[V] = \begin{bmatrix} V_1 & V_2 \end{bmatrix} \qquad (12)$$

$$[PD] = \begin{bmatrix} PD_1 & PD_2 & & PD_n \end{bmatrix}^T \qquad (13)$$

$$i = 1, 2 \; k = 1, ..., n$$

Assuming that the partial discharge is from one input (place), which is can be (j), so the other PDs will be equal to zero. The output between the bushing and the neutral will be:

$$V_1 = H_{1j} \times PD_j \qquad (14)$$

$$V_2 = H_{2j} \times PD_j \qquad (15)$$

The TF (PD) will be:

$$PD_j = (1/H_{1j}) \times V_1 \qquad (16)$$

$$PD_j = (1/H_{2j}) \times V_2 \qquad (17)$$

By definition (measuring) of V1, V2 and the sectional winding TF H_{ik}, it is not difficult to calculate PD as a value and to localize its place. PD can be calculated by equations (16) and (17) in frequency domain as two signals can be measured at the bushing of the transformer and at the neutral

$$PD_j(j\omega) = (1/H_{1j}(j\omega)) \times V_1(j\omega) \qquad (18)$$

$$PD_j(j\omega) = (1/H_{2j}(j\omega)) \times V_2(j\omega) \qquad (19)$$

The importance of equations (18) and (19) as system that: Calculating the same PD with different TF H_{1j}, H_{2j}j and the same inputs PD_j allow localizing, minimizing the measuring errors and avoiding the noise as it is comparable with high accuracy. In other wards enable to minimize the test time and to define with high accuracy the mechanical deformed parts of the insulations in the transformer.

These techniques also, allow to spilt the transfer function $TF(w)$ into a sectional winding TF a long the windings. Then to define PD Localization according to the measurement data and results. The coil of a transformer is divided in numerous winding sections. The PD at an unknown origin generates a signal which travels through the winding sections to the high voltage bushing and to e.g. the neutral or star point [12],[13]. The bushings as well as the neutral point are accessible points or PD measurements and the signal can be recorded.

C. Measurements and Experiments Setup:

The measuring process sequences using the TF are illustrated in Fig. 3. This basic simple flowchart shows that the results of current measurements are usually compared with the reference fingerprints. If there is no significant deviation of the compared functions, there should be no change inside the transformer on its conditions during the operating and service time. Denoting that unfortunately, "fingerprints" of old transformers are rarely available. Therefore, a recommendation to Electrical Industrial Sector and the Electrical Installation Companies to add the FRA tests for all the transformers as a reference data "fingerprint" of the transformer manufactured and installed conditions, with which, the regular and failure tests can be compared and refereed.

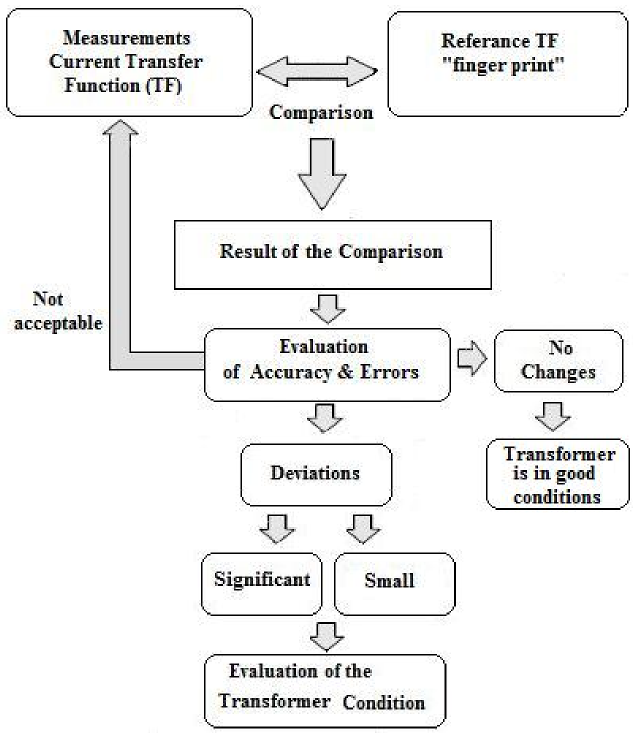

Fig. 3. :Simple flowchart for evaluating transformer conditions

If no fingerprint and no identical test object exists, the symmetric properties of the core-and-coil-assembly can be used to compare several measurements (construction-based evaluation). Then, transformer is in good conditions. Mostly, mechanical damages affect only one of the three phases. A separate examination of all phases will detect the differences of one phase towards the others, [14],[16]. The three evaluation procedures can also be taken for fault identification and localizations. After comparing the results and considering the expected accuracy of the measurement, then it should be decide, if the results deviate significantly or just a small one. The measurement has to be evaluated in detail.

The measurements have been performed in the laboratory of the Schering- Institute, Leibniz University of Hanover, Germany, on a distribution transformer 400 V / 10 kV, 100 kVA. The mechanical deformation of the isolation and PD measurements within the transformer winding associated by frequency range from a few Hz to hundreds MHz. Sweep Frequency Response Analyzer for the power transformer core and winding diagnosis by Omicron has been installed and used as it shown in figure 4

Fig. 4. :Measuring of the transfer functions.

The measurements are compared with a “fingerprint”, which has to be determined firstly as reference. But, on this case, the manufacturing “fingerprints” for this old transformer (Fig. 4) is absent. The decision was taken to compare the pashas TF measuring results together. But it important to note here that we assume that the loads on the phases were almost in symmetrical operation mode.

Analyzing the results in Fig. 5 shows that there is nearly no changes at the high frequencies but a remarkable and significant deviation at low frequencies between the reference TF and the current measurement one. Deviations between the reference TF and the current TF indicate PD and failure.

For more comparable analysis, to achieve high accuracy in estimation of the PD localization a great need to other TF measurements to be compared with the same type of transformer without any failure. The results are illustrated in

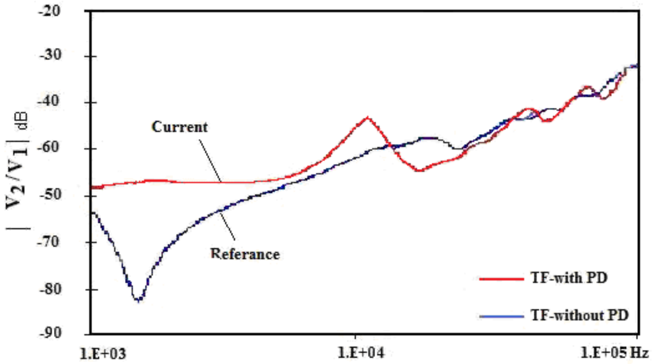

Fig. 5. :The Winding TF for the transformer with faults (PD) and without faults (PD)

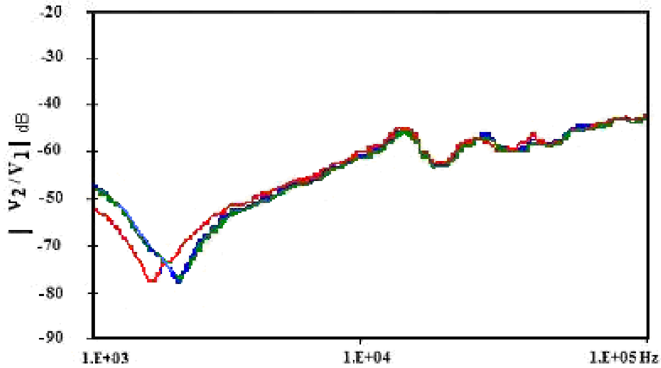

Fig. 6. :The Winding Transfer Function for the normal transformer

Figure 6 It is clearly that TF of the normal transformer is very similar to the reference TF of the phase. Also, the figure 6 shows that even every phase in the same transformer has its own unique fingerprints. The measurements of TF where made in an offline mode. For online measurement, instead of the delta impulse a steep switching impulse can be used.

D. Remodeling the Frequency Response of the Winding:

his modeling is according to the operation condition which appears after time of working and aging process. The model is based on the FRA measurements. The FRA measured the impedance transformer winding in frequency range. Therefore the transformer can be considered like a linear system due to the application of a low voltage signal. It is possible to know how the transformer behaves. When a fault or PD occurred the frequency is changing because the measure of the system represents the behavior of the machine. According to Pleite and Gonzlez [17],[18] the transformer model can be sectioned into cells or parts as it shown in Fig. 6. The groups of i cells represent a general component (core and winding) and every cell contain a number winding sections. A unique cell inside these groups will represent a specific deviation on bandwidth of the frequency response and a specific part inside these components. This will be identifying the mechanical defect that cause a behavior such as a PD or fault source.

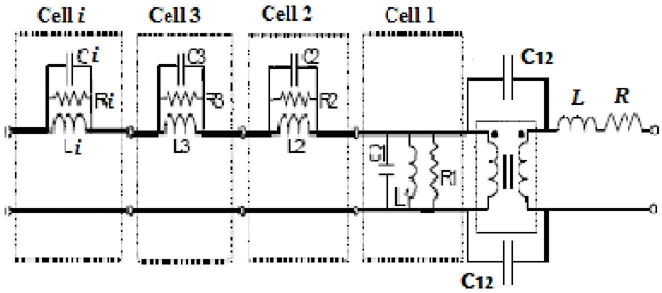

Fig. 7. :Remodeling of the transformer as a group of cells according to FRA measurements.

The experiment measures the impedance of the winding and the equivalent impedance of the cell, Fig. 7, the same relations can be obtained. In this case the L_i parameter of the cell reproduces the main inductance of the transformer, the C_i parameter reproduces the main capacitance of the winding and the R_i parameter reproduces the resonant point between $L._s$ and $C._s$ [18].

The values of each cell parameters are calculated from the FRA response at the assigned frequency.

According to the model shown in Fig. 7 , the equivalent admittance on n cell can be calculated by the flowing equation;

$$y_n(w, r_n, C_n, L_n) = \frac{1}{R_n} + jwC_n + \frac{1}{jwL_n} \qquad (20)$$

Where n =1,,i The parameters of the model in equation (20) can be calculated with math lab or any suggested program.

The main objective of this remodeling is to link the parts inside the transformer the core and windings with its frequency response and obtain a correlation between the changes in the internal parts and their reflections on the response. Correspondingly these changes supposed to indicate the new appearance of PD sources (hot spots) as the admittance (impedance) of the windings will be changed.

II. Conclusion

A mathematical model for transformer interior deformation and PD localization has been developed in this paper. A recommendation to Industrial sector and the electrical installation companies to add the FRA tests for all the transformers as a reference data "fingerprint" of the transformer manufactured conditions as an indicator with which the normal and failure test can be compared. The Schemes of flowchart for evaluating transformer conditions to achieve robust evaluating presses has been illustrated. A procedure of transformers remodeling according to measurements of their internal conditions by the FRA has been presented. This method of remodeling allows the determining of the mechanical defects by means of the sectional transfer function, where PD signal will be localize at the true defected origin. These techniques allow mathematically to spilt the Transfer function into a sectional winding transfer function a long the windings. The splitting techniques of the Transfer function into a sectional winding transfer function a long the windings have been tested and approved to localize the defected origin.

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References

[1] A. oguz Soysal and Adam Semlyen *Practical Transfer Function Estimation and Its application to Wide Frequency Range Representation of Transformers*, IEEE Transactions on Power Delivery, Vol. 8, No. 3, July 1993.

[2] R. Pintelon , Guillaume , Y.P. Rolain , J. Schoukens and H. Van hamme, *Parametric Identification of Transfer Functions in the Frequency Domain-A Survey*, IEEE Transactions on Automatic Control. Vol. 39, No. 11. November 1994.

[3] A. Akbari, P. Werle, H. Borsi and E. Gockenbach, *Transfer Function-Based Partial Discharge Localization in Power Transformers: A Feasibility Study*, IEEE Electrical Insulation Magazine, Vol. 18, No. 5, pp. 22-33.2002.

[4] A. Oguz Soysal and Adam Semlyen, *State Equation Approximation of transfer Matrices and Its Application to the Phase domain calculation of Electromagnetic Transients*, IEEE Transactions on Power Systems, Vol. 9, No. 1, February 1994.

[5] Islam, S.M. Coates, K.M. Ledwich, G., *Identification of High Frequency Transformer Equivalent Circuit Using Matlab from Frequency Domain Data*, Industry Applications Conference, 1997 IEEE Volume: 1, On page(s): 357-364 vol.1

[6] Wenzel, D. Borsi, H. Gockenbach, E.,*Partial discharge recognition and localization on transformers via fuzzy logic*

[7] P. Werle, A. Akbari, H. Borsi, E. Gbckenbach, *Enhanced Online PD Evaluation on Power Transformers using Wavelet Techniques end Frequency Rejection Filter for Noise Suppression*, 14th International Symposium on Electrical Insulation (ISEI), Boston, USA, pp. 195-198, 2002

[8] A. Akbari, P. Werle, H. Borsi, E. Gockenbach, *A New Method for On-line Measurement and Evaluation of Partial Discharge in Power Transformers Using Fibre-Optic Transmission 17*, Power System Conference (PSC), Tehran, Iran, No. 49-E-TRN-330.2002

[9] E. Gockenbach, M. Farahani, *Partial Discharge Measurement as Diagnostic Tool for Insulation System in High Voltage Rotating Machines*, CIGRE SC A1 & D1 Colloquium Korea 2007, pp. 130-137.

[10] A. Setayeshmehr, C. Eichler, A. Akbari, H. Borsi, E. Gockenbach, *Condition Evaluation of Oil-Pressboard Insulation by Fourier Transform Of Time Domain Dielectric Response*, 20th Nordic Insulation Symposium (NORD-IS), Lyngby, Denmark ,2007,pp.169-172.

[11] A. Setayeshmehr, A. Akbari, H. Borsi, E. Gockenbach, I. Fofana, *Winding Diagnostic by On-line Transfer Function Determination via Power Transformer Bushing Tap* 15th International Symposium on High Voltage Engineering (ISH), Ljubljana, Slovenia, 2007;T7-536.

[12] J. Szczechowski, H. Borsi, E. Gockenbach, *Partial Discharge Measurement and Localization on Power Transformers*, 15th International Symposium on High Voltage Engineering(ISH), Ljubljana,Slovenia, 2007, T7 659.

[13] A. Setayeshmehr, I. Fofana, A. Akbari, H. Borsi, E. Gockenbach, *Effect of Temperature on Dielectric Response of Transformer Insulation*, 15th International Symposium on High Voltage Engineering (ISH), Ljubljana, Slovenia, 2007, T8-537.

[14] A. Setayeshmehr, A. Akbari, H. Borsi, E. Gockenbach, *On-line Monitoring and Diagnosis of Power Transformers Bushings*, IEEE TDEI Vol.13, No. 3, 2006 p. 608-615.

[15] A. Setayeshmehr, J. Abdallah, H. Borsi and E. Gockenbach. (2008), *Evaluation of Transformer Dielectric Response at Different Equilibrium Conditions and Temperatures*, International conference on modeling and simulation (AMSE, MS-08) Petra Jordan, 2008.

[16] K. Feser, J. Christian, T. Leibfried, A. Kachler, C. Neumann U. Sundermann, M. Loppacher, *The Transfer Function Method for Detection of Winding Displacements on Power Transformers after Transport, Short Circuit or 30 Years of Service*, High Voltage Test "HAEFELY" by Cigree 2000.

[17] C. Gonzalez, J.Pleite, R.A Salas,.; J. Vazquez, *Transformer Diagnosis Approach using Frequency Response Analysis Method*, IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics Issue , 6-10 Nov. 2006 Page(s):2465 – 2470.

[18] J. Pleite, E. Olas, A. Barrado, A. Lzaro, J. Vquez, *A procedure to model the frequency response*, March 2002 SAC '02: Proceedings of the 2002 ACM symposium on Applied computing.

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