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Quantization of Impedance Stability in Frequency Domain

Soheyl Soodmand
dept.electrical & electronic engineering
university of bristol
Bristol, United Kingdom
soheyl.soodmand2@gmail.com

Kevin A. Morris
dept.electrical & electronic engineering
university of bristol
Bristol, United Kingdom
kevin.morris@bristol.ac.uk

Mark A. Beach
dept.electrical & electronic engineering
university of bristol
Bristol, United Kingdom
m.a.beach@bristol.ac.uk

***Abstract*—A method based on Sample Standard Deviation (SSD) is suggested here to quantify impedance stability in frequency domain. Firstly, impedance instability factor, δ_T, is introduced as an indicator of that could be used for impedance stability quantifications of measured or simulated impedance data of Radio Frequency (RF) and high-power devices. The method is used then for a generic real/imaginary impedance trajectory as an example to clarify calculation process. Finally, the introduced approach has been used to quantify impedance stabilities in some RF devices such as stable impedance antenna of 5G In-Band Full Duplex (IBFD) Transceivers, microstrip low-pass filter and hybrid coupler. Also, suitable efficiency of the method to follow up correct design direction to smoothen impedance of an antenna is realized.**

Keywords— microwave measurement, impedance stability, RF devices, high power, antennas, IBFD.

I. INTRODUCTION

Acquisition of impedance stability in frequency domain is an important feature to retain suitable efficiency in systems such as: 5G In-Band Full Duplex Transceivers (IBFD) [1]–[3], biotelemetric devices [4], [5], body-Centric antennas [6], [7], ultra-wideband (UWB) systems [8], impedance-matching tuners [9], nanoantenna for THz communication [10], power amplifiers [11], mechatronic systems [12], microwires [13], power inverters/generators [14], grid distribution networks [15], and high frequency oscillation eliminators in medium-voltage direct-current (MVDC) systems [16]. Examples of some of these systems are shown in Fig. 1. To the best of the authors knowledge there is not any specific mathematical method in the literature to quantify impedance stability in frequency domain and normally visual methods are carried out for these assessments. Quantifying impedance stability could help designers to follow up efficient design direction when a stable impedance is needed.

In this paper, Section II, a method based on Sample Standard Deviation (SSD) is suggested to quantify impedance stability in frequency domain. SSD is used as an indicator by introducing impedance instability factor, δ_T, of that could be used for impedance stability quantifications of measured or simulated impedance data of Radio Frequency (RF) and high-power devices. The method is used then in Section III for a generic form of impedance as an example to clarify δ_T calculation process. In Section IV, the introduced approach has been used to quantify impedance stabilities in some RF devices. Finally, a conclusion is given in Section V.

II. SAMPLE STANDARD DEVIATION AND IMPEDANCE INSTABILITY FACTOR

Sample Standard Deviation (δ) in mathematics is a quantity expressing by how much the members of a data group differ from the data mean value, M, for the group. There are formulas to calculate δ value for both continuous data function [17] and discrete data group [18]. Normally impedance trajectories of RF devices do not follow a known mathematical function in the real world, so the discrete data formula is considered here to start which is expressed [18] as

$$\delta = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - M)^2}\,. \tag{1}$$

where $\{x_1, x_2, \ldots, x_N\}$ are the observed data values of the sample items, N is the number of observations in the sample and $M = (x_1 + x_2 + \ldots + x_N)/N$ is the mean value of the observed data group. Accuracy of δ calculation increases when N increases. The δ value is used here as an indicator to quantify impedance instability in frequency domain. The δ parameter in (1) is rewritten for real (Re) and imaginary (Im) impedances of the device (high power, RF, or antenna), in a defined frequency bandwidth, respectively, as below

$$\delta_{Re} = \sqrt{\frac{1}{N_f-1}\sum_{i=1}^{N_f}\left(Z_{i(Re)} - M_{Re}\right)^2}\,. \tag{2}$$

$$\delta_{Im} = \sqrt{\frac{1}{N_f-1}\sum_{i=1}^{N_f}\left(Z_{i(Im)} - M_{Im}\right)^2}\,. \tag{3}$$

N_f indicates the number of frequencies wherein either real or imaginary impedance are sampled (observed), $Z_{i\,(Re)}$ and $Z_{i\,(Im)}$ indicate the value of observed real and imaginary impedances respectively at each f_i frequency (i=1, 2, …, N). M_{Re} and M_{Im} are mean values of sampled real and imaginary impedances, respectively. δ_{Re} and δ_{Im} indicates how much their relevant impedance trajectory differ from its mean value in a defined frequency bandwidth. Looking to the formulas from dimensional point of view both δ_{Re} and δ_{Im} have Ohm (Ω) unit. However, total value of δ, so called impedance instability factor of δ_T, is defined as a Root Mean Square (RMS) of δ_{Re} and δ_{Im} to quantify instability of the whole complex impedance as

$$\delta_T = \delta_{Total} = \delta_{RMS} = \sqrt{\frac{{\delta_{Re}}^2 + {\delta_{Im}}^2}{2}}\,. \tag{4}$$

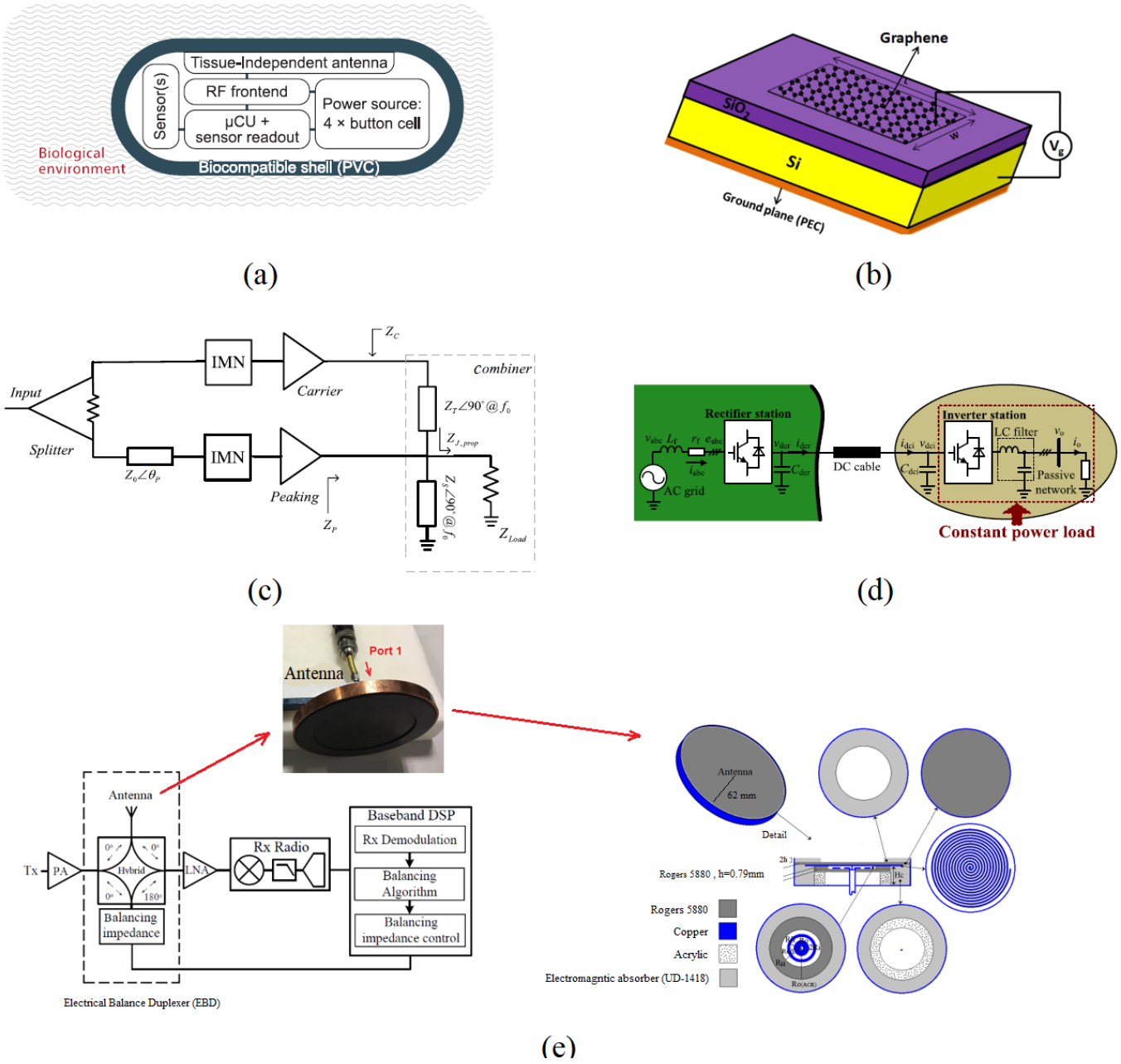

Fig. 1. Some example of systems wherein impedance stability in frequency domain is needed, (a) Wireless pill-shaped device for biotelemetry applications [5], (b) Graphene plasmonic nanoantenna for THz communication [10], (c) Doherty power amplifier with wideband combiner [11], (d) Two-terminal voltage source converter of high voltage direct current system [14], (e) In-Band Full Duplex (IBFD) RF front-end system with stable impedance antenna designed by the authors at University of Bristol.

δ_T has an ohm (Ω) dimension, also δ_T = 0 Ω indicates no impedance variations in frequency domain which is not normally possible in practice for a real RF or high-power device due to physics of electromagnetic waves. Based on the above discussion higher and lower impedance instability factors indicate lower and higher impedance stabilities, respectively and the value of δ_T could be used as an indicator to quantify impedance instability in frequency domain for antennas, RF and high-power devices.

III. An Example to Clarify δ_T Calculation Process for a Generic Form of Impedance Trajectory

A generic set of real and imaginary trajectories of device impedance in a defined frequency bandwidth are shown in Fig. 2 for three observation frequencies of f_i i.e. (i = 1, 2, 3) or N_f= 3.

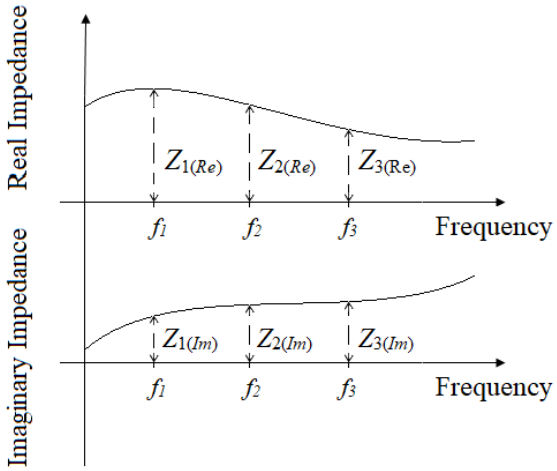

Fig. 2. Generic set of real and imaginary trajectories of antenna input impedance.

Real and imaginary impedances at frequency of f_i are denoted by $Z_{i\,(Re)}$ and $Z_{i\,(Im)}$, respectively. In the first step, mean value of observed $Z_{i(Re)}$ and $Z_{i(Im)}$ impedances are calculated respectively as $M_{Re} = (Z_{1(Re)} + Z_{2(Re)} + Z_{3(Re)}) / N_f$ and $M_{Im} = (Z_{1(Im)} + Z_{2(Im)} + Z_{3(Im)}) / N_f$, Fig. 2. Thereafter the below expressions from (2) and (3) are calculated as

$$\sum_{i=1}^{3}\left(Z_{i(Re)} - \mu_{Re}\right)^2 = \left(Z_{1(Re)} - M_{Re}\right)^2 + \left(Z_{2(Re)} - M_{Re}\right)^2 + \left(Z_{3(Re)} - M_{Re}\right)^2 . \quad (5)$$

$$\sum_{i=1}^{3}\left(Z_{i(Im)} - M_{Im}\right)^2 = \left(Z_{1(Im)} - M_{Im}\right)^2 + \left(Z_{2(Im)} - M_{Im}\right)^2 + \left(Z_{3(Im)} - M_{Im}\right)^2 . \quad (6)$$

Now the resulted values from (5) and (6) replaced respectively in (2) and (3) with N_f=3 to calculate δ_{Re} and δ_{Im}. Finally, the calculated δ_{Re} and δ_{Im} values are replaced in (4) to obtain impedance instability factor of δ_T. It needs to be mentioned that choosing N_f = 3 causes a low accuracy in δ_T calculations and in practice higher number of observation frequencies i.e. higher N_f is needed for precise calculation, for example N_f = 500 is used in this paper for calculations. The described method could be used to quantify impedance instability.

IV. Assessments

Firstly, impedance trajectories of some RF devices have been evaluated in this section to calculate their impedance instability factor. These are three RF devices: a stable impedance antenna for IBFD applications (Fig. 1(e)), a microstrip low pass filter (Fig. 3) and a microstrip hybrid coupler (Fig. 3). Measured impedances of these devices by Vector Network Analyzer (VNA) are shown in Fig. 4 where their calculated δ_{Re}, δ_{Im} and impedance instability factor of δ_T at 2GHz - 3.5GHz range are

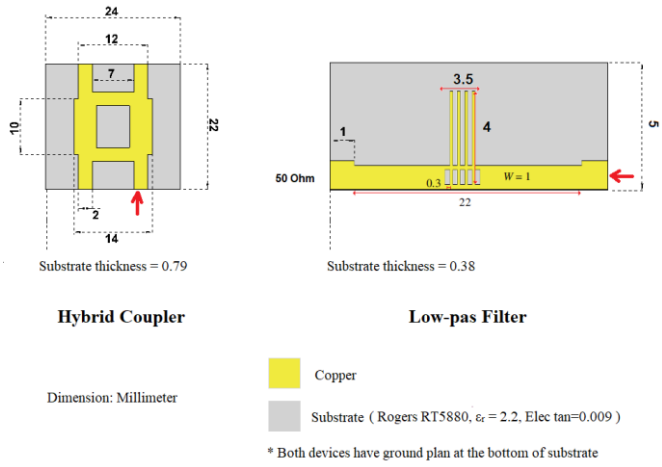

Fig. 3. Assessed hybrid coupler and low-pas filter.

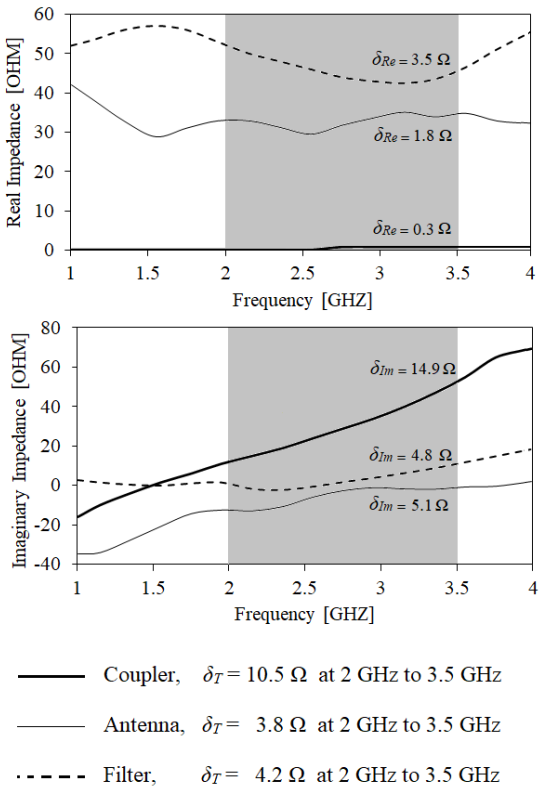

Fig. 4. Impedance and δ_T factor of antenna (Fig. 1(e)), coupler (Fig. 3) and low pass filter (Fig. 3).

calculated as well based on the method and formulas described in Section II and Section III, indicating how much their impedance trajectory differ from its mean value in the defined frequency bandwidth. Measurements are performed at the port shown by red arrow (Fig. 1(e) and Fig.3) while for coupler and filter the other ports are terminated by 50 Ω broadband load.

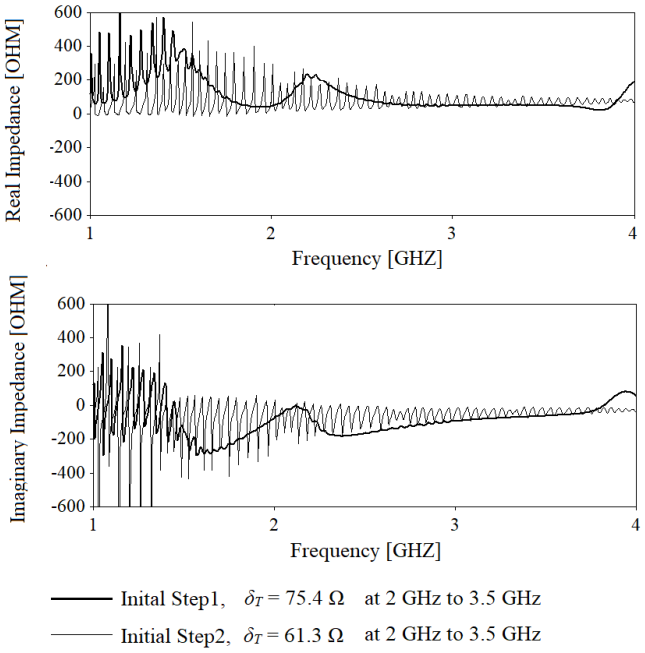

Fig. 5. Impedance and δ_T factor of antenna at the initial steps of design.

Secondly, in the cases wherein the designer faces with very dense impedance variation in the design process, the introduced method could help to follow up more efficient design direction. An example of impedance trajectory with dense impedance variation is shown in Fig. 5 which the authors faced during initial design steps of the stable impedance antenna shown in Fig1(e). Final smoothed impedance of the antenna, with lower impedance instability indicator of δ_T, is achieved following up the presented impedance stability quantization method (Section II and Section III) to reduce δ_T indicator in step-by-step modifications and the result is given in Fig. 4, confirming efficiency of the introduced method to achieve stable impedance.

The design process of the stable impedance antenna is given with more details in a separate paper and the focus of this paper here was on quantization of impedance stability in frequency domain by introducing impedance instability factor, δ_T, in theory and then assessment based on measured data of some practical devices.

V. CONCLUSION

Sample Standard Deviation (SSD) based method is suggested in this paper to quantify impedance stability in frequency domain. Impedance instability factor, δ_T, is introduced as an indicator of that could be used for impedance instability quantifications of measured and simulated impedance data of Radio Frequency (RF) and high-power devices. The method is used then for a generic real/imaginary impedance trajectory to clarify calculation process. The introduced method then has been used to quantify impedance instabilities in some RF devices: a stable impedance antenna for IBFD applications, a low pass filter, and a microstrip hybrid coupler. Also, suitable efficiency of the method to follow up correct design direction to smoothen impedance of an IBFD antenna is realized.

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