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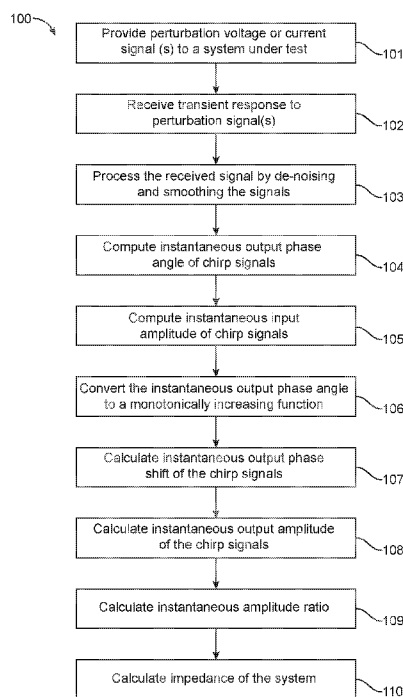


FIG. 1

(57) Abstract: The invention discloses a method for measuring impedance of a system under test. The method includes multiple, high bandwidth, short duration chirp signals having dissimilar phase to estimate impedance. The method includes generating at least one chirp signal for perturbing the system under test and receiving transient response signals from the system. The received signal is then processed and analyzed to compute the instantaneous amplitude ratio and instantaneous phase shift. The impedance of the system is measured as a function of the instantaneous amplitude ratio and instantaneous phase shift. The method includes dual and triple phase shifted chirp signals to obtain the impedance profile. The system may be a linear system or nonlinear system. The method may be implemented on smaller processors with relatively low computational power and measures the impedance within 3 to 7 seconds for perturbation signals of frequency ranging from 0.1 Hz to 10 kHz.



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**METHOD FOR IMPEDANCE MEASUREMENT USING MULTIPLE
PHASE SHIFTED CHIRP SIGNALS**

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims priority to Indian Patent Application No. 201941009170 entitled METHOD FOR IMPEDANCE MEASUREMENT USING MULTIPLE PHASE SHIFTED CHIRP SIGNALS filed on 8 March, 2019.

FIELD OF THE INVENTION

[0002] The disclosure relates generally to impedance measurements and in particular to methods for impedance measurements using multiple phase shifted chirp signals.

DESCRIPTION OF THE RELATED ART

[0003] Battery and fuel cell technology have gained popularity in the last decade owing to the emergence of portable electronics, electric drives, micro-grid technology etc. Li-ion batteries in particular have been commercially viable due to their higher energy densities and longer lifetimes. However they are subject to both performance and capacity degradation which impact their lifetime irreversibly. Although it is impossible to reclaim lost capacity, periodic diagnosis and subsequent management can prolong the lifetime of batteries and fuel cells. Impedance is predominately used to characterize electrochemical energy systems such as fuel cells, batteries, super capacitors etc. Impedance is an important diagnostic feature finding applications in various domains ranging from material science, analytical chemistry and biological systems among others. Electrochemical Impedance Spectroscopy (EIS) is the most popular method used for impedance measurement. However, EIS method is time intensive and requires sophisticated and bulky instrumentation, thus making it unsuitable for online or onboard applications. Also, it is difficult to characterize faster systems whose properties change during the course of the EIS analysis.

[0004] A method for impedance measurement using chirp signal injection is disclosed in the US patent US9562939B2. The European patent EP2314217B1 discloses a method for performing impedance spectroscopy by fast measurement of frequency response of biological object having dynamically varying in time parameters. The method includes Fourier transform to obtain a complex impedance spectrum. A highly time resolved impedance spectroscopy that enhances the measurement of the dynamics of non-stationary systems with enhanced time resolution is disclosed in US patent US6556001B1. A method of electrode impedance measurement that includes modified short time Fourier transformation (STFT) for analysis of the voltage perturbation signal and the current response for the determination of impedance spectrum has been disclosed in “Determination of electrode impedance by means of exponential chirp signal”, Darowicki et al. (2004). Prior art methods to measure impedance require a large data set, are computationally intensive, and have issues in frequency localization. Further, the prior art methods are sensitive to system non linearity and noise and includes computationally intensive algorithms. The present disclosure describes a method of impedance measurement that overcomes some of the drawbacks of existing methods.

SUMMARY OF THE INVENTION

[0005] In various embodiments, a method for measuring impedance of a system is disclosed herein.

[0006] In one embodiment of the disclosure, the method includes generating at least one chirp signal for perturbing the system under test, perturbing the system under test with at least one chirp signal, receiving transient response signals from the system, processing the received signals to remove quantization errors and external interferences, analyzing the response to obtain impedance spectrum by assessing the amplitude and phase angle of the system from the response data and calculating impedance of the system. The perturbation chirp signal is a voltage or current signal. The response is either

a voltage or a current signal. The amplitude and phase angle of the system is assessed by computing instantaneous input amplitude of chirp signals, computing instantaneous output phase angle of chirp signals, converting the instantaneous output phase angle to a monotonically increasing function, where the function increases from zero to infinity, calculating instantaneous output phase shift of the chirp signals, calculating instantaneous output amplitude of the chirp signals and calculating amplitude ratio. The amplitude ratio is the ratio of the instantaneous output amplitude to instantaneous input amplitude. The impedance is calculated as a function of the instantaneous amplitude ratio to the instantaneous phase shift.

[0007] In various embodiments, the chirp signal is a dual chirp signal or triple chirp signal. In few embodiments, the signals in dual chirp signals are separated by a predefined phase difference. In few embodiments, the signals in triple chirp signals are separated by a predefined phase difference with predefined DC levels.

[0008] In various embodiments, the perturbation and the response signal is a combination of either voltage or current signals.

[0009] In various aspects, the instantaneous phase shift of dual chirp signals and triple chirp signals are calculated from the initial phase angle and instantaneous phase angle of the input chirp signals. In various aspects, the instantaneous amplitude ratio for dual chirp signals and triple chirp signals are also calculated.

[0010] In various aspects, the impedance Z for dual and triple chirp signal is calculated from the instantaneous amplitude ratio and instantaneous phase shift. In few embodiments, the time taken to measure the impedance ranges from 3 – 7 seconds for perturbation signals of frequency ranging from 0.1 Hz to 10 kHz. In some embodiments, the impedance is measured for perturbation signals of frequency ranging from 0.001 Hz to 10 kHz.

[0011] This and other aspects are disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawings, in which:

[0013] FIG. 1 illustrates a method of measuring impedance of a system under test.

[0014] FIG. 2A shows a system under test in series with a known resistance.

[0015] FIG. 2B shows a system under test in parallel with a known resistance.

[0016] FIG. 3 shows the master circuit used to generate the test circuits used in the study.

[0017] FIG. 4 shows the Simulink® model to generate data for validation of the dual chirp algorithm.

[0018] FIG. 5A shows simulated impedance profile obtained from dual chirp against theoretical impedance for the test circuit 1.

[0019] FIG. 5B shows simulated impedance profile obtained from dual chirp against theoretical impedance for the test circuit 2.

[0020] FIG. 5C shows simulated impedance profile obtained from dual chirp against theoretical impedance for the test circuit 3.

[0021] FIG. 6A shows the schematic for dual chirp implementation with current perturbation on hardware.

[0022] FIG. 6B shows the voltage response obtained from circuit 1 through the schematic shown in FIG 6A.

[0023] FIG. 7 illustrates the Simulink® model used to generate data for validation of the modified dual chirp algorithm.

[0024] FIG. 8 shows the flowchart for the in-silico implementation of modified dual chirp analysis

[0025] FIG. 9A shows the comparison of simulated impedance profiles obtained from modified dual chirp against theoretical impedance and dual chirp technique for the test circuit 1.

[0026] FIG. 9B shows the comparison of simulated impedance profiles obtained from modified dual chirp against theoretical impedance and dual chirp technique for the test circuit 2.

[0027] FIG. 9C shows the comparison of simulated impedance profiles obtained from modified dual chirp against theoretical impedance and dual chirp technique for the test circuit 3.

[0028] FIG. 10 shows the schematic diagram for hardware implementation of modified dual chirp analysis method.

[0029] FIG. 11A shows the impedance profiles for modified dual chirp approach obtained through the experimental hardware setup compared against the theoretical impedance and those obtained from simulation for the test circuit 1.

[0030] FIG. 11B shows the impedance profiles for modified dual chirp approach obtained through the experimental hardware setup compared against the theoretical impedance and those obtained from simulation for the test circuit 2.

[0031] FIG. 11C shows the impedance profiles for modified dual chirp approach obtained through the experimental hardware setup compared against the theoretical impedance and those obtained from simulation for the test circuit 3.

[0032] FIG. 12 illustrates the Simulink® model used to generate data for validation of the triple chirp method.

[0033] FIG. 13A illustrates DC shift of output signal.

[0034] FIG. 13B illustrates the magnitude of impedance estimated using trip chirp algorithm.

[0035] FIG. 13C illustrates the angle of impedance estimated using trip chirp algorithm.

[0036] FIG. 14A illustrates impedance profiles generated using triple chirp method for circuit 1.

[0037] FIG. 14B illustrates impedance profiles generated using triple chirp method for circuit 2.

[0038] FIG. 14C illustrates impedance profiles generated using triple chirp method for circuit 3.

[0039] FIG. 15 shows the flowchart for the in-silico implementation of triple chirp algorithm.

[0040] FIG. 16 shows the comparison of impedance profile estimated using triple chirp analysis method after additional denoising with interval halving in comparison with the theoretical impedance.

[0041] Referring to the drawings, like numbers indicate like parts throughout the views.

DETAILED DESCRIPTION

[0042] While the invention has been disclosed with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt to a particular situation or material to the teachings of the invention without departing from its scope.

[0043] Throughout the specification and claims, the following terms take the meanings explicitly associated herein unless the context clearly dictates otherwise. The meaning of "a", "an", and "the" include plural references. The meaning of "in" includes "in" and "on." Referring to the drawings, like numbers indicate like parts throughout the views. Additionally, a reference to the singular includes a reference to the plural unless otherwise stated or inconsistent with the disclosure herein.

[0044] The present invention in its various embodiments discloses a method for measuring the impedance profile of a system under test. The method may be embedded in a small device capable of perturbing the system under test with the test signal and acquiring the response. The response is subsequently used to estimate the impedance profile of the system under test.

[0045] In various embodiments, a method **100** as shown in FIG. 1 for measuring impedance of a system includes the following steps. In step **101**, the system under test is perturbed with at least one chirp input signal. In step **102**, a response from the system, which is either a voltage or a current signal, is acquired. In various embodiments, a transient response including magnitude and phase information of the system is acquired from the system. The response of the system includes current signal when the input is a voltage signal or voltage signal when the input is a current signal. In step **103**, the received signal is processed. In some embodiments, a two-stage filtering process is used.

In some embodiments, processing the received signal includes de-noising and smoothing the signals.

[0046] The obtained response is denoised and a soft thresholding is applied to achieve denoising without significant signal attenuation. In some embodiments the soft thresholding may adopt different levels of thresholds for different intervals in data. Further, the denoised signal is smoothed to remove low amplitude noise which affects the impedance profiles to obtain a significantly clean impedance plot. In one embodiment, chirp input signals are de-noised using wavelet filter. In one embodiment, symlet 4 wavelet is used for de-noising. In one embodiment, the denoised signals are smoothed using a moving average filter. The response of the system is then analyzed to obtain impedance spectrum using chirp analysis algorithm by assessing the magnitude and phase information of the system from the response data. Further, the method includes computing instantaneous output phase angle of chirp signals as in step **104**.

[0047] In various embodiments, chirp analysis algorithm includes current response for voltage perturbation, voltage response for current perturbation, voltage response for voltage perturbation and current response for current perturbation for both dual and triple chirp signals.

[0048] The method further includes computing instantaneous input amplitude of chirp signals as in step **105**. The instantaneous output phase angle is converted to a monotonically increasing function in step **106**. The function F , increases from zero to infinity. Further, in step **107** instantaneous output phase shift of the chirp signals is calculated. The instantaneous output amplitude of the chirp signals is computed in step **108**. Further, the instantaneous amplitude ratio is calculated in step **109**. The instantaneous amplitude ratio is calculated as the ratio of instantaneous output amplitude to instantaneous input amplitude of the signal. In step **110**, impedance of the system, as a

function of the instantaneous amplitude ratio to the instantaneous phase shift is calculated.

[0049] In various embodiments, the step **101** in method **100** includes a plurality of chirp input signals. The plurality of chirp input signals are of high bandwidth, short duration signals having dissimilar phases. In some embodiments, the chirp signal is a dual chirp signal or a triple chirp signal. In some embodiments, dual phase shifted chirp signal that includes two identical chirp signals separated by a predetermined phase shift are used. In one embodiment, two exponential voltage signals with frequency range of 0.1Hz to 10 kHz are used as chirp input signals. In another embodiment, two exponential current signals with frequency range of 0.1Hz to 10 kHz is used as an input signal. In some embodiments, impedance is measured for perturbation signals of frequency ranging from 0.001 Hz to 10 kHz. In some embodiments, triple chirp signals separated by a predefined phase difference with predefined DC levels are used.

[0050] In various embodiments, the step **102** in method **100** includes measuring the response of the system as either a voltage or a current signal. For a voltage perturbation signal, the response is acquired as a voltage signal in one embodiment while it is acquired as a current signal in another. In yet another embodiment, the response is acquired as a voltage signal for a current perturbation signal.

[0051] In various embodiments, the step **107** in method **100** includes computing instantaneous phase shift of chirp signals using the following equations if two input chirp signals are provided as an input to the system under test:

$$\Psi(t) = \tan^{-1} \left(\frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \right) - \phi(t) \text{-----}(1)$$

where,

$\Psi(t)$ represents instantaneous phase shift,

$\phi_{1,0}$ and $\phi_{2,0}$ represents initial phase angle for the input dual chirp signals 1 and 2 respectively,

$\emptyset(t)$ represents instantaneous phase angle of the input dual chirp signals 1 and 2, and

$K(t)$ represents the ratio of output voltage of signal 1 to output voltage of signal 2.

[0052] In various embodiments, the step **107** in method **100** includes computing phase shift of chirp signals using the following equations if three input chirp signals are provided as an input to the system under test:

$$\Psi(t) = \tan^{-1} \left(\frac{k(t) * (\cos(\emptyset_{2,0}) - \cos(\emptyset_{3,0})) + (\cos(\emptyset_{3,0}) - \cos(\emptyset_{1,0}))}{k(t) * (\sin(\emptyset_{2,0}) - \sin(\emptyset_{3,0})) + (\sin(\emptyset_{3,0}) - \sin(\emptyset_{1,0}))} \right) - \emptyset(t) \text{-----}(2)$$

where,

$\Psi(t)$ represents instantaneous phase shift,

$\emptyset(t)$ represents instantaneous phase angle of the input triple chirp signals 1, 2 and 3,

$\emptyset_{1,0}$ represents initial phase angle for the input chirp signal 1,

$\emptyset_{2,0}$ represents initial phase angle for the input chirp signal 2,

$\emptyset_{3,0}$ represents initial phase angle for the input chirp signal 3.

[0053] In various embodiments where the response is a voltage signal, the step **109** in method **100** includes computing instantaneous amplitude ratio of two chirp signals using the following equations:

$$A_R(t) = \frac{V_{out}^1(t)}{A_{in} \cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t))} \text{-----}(3)$$

where,

$A_R(t)$ represents instantaneous amplitude ratio,

$\Psi(t)$ represents instantaneous phase shift,

$\emptyset(t)$ represents instantaneous phase angle of the input dual chirp signals 1 and 2,

$\emptyset_{1,0}$ represents initial phase angle for the input chirp signal 1,

A_{in} represents amplitude of chirp signals,

$V_{out}^1(t)$ represents output voltage response of signal 1.

[0054] In various embodiments where the response is a current signal, the step **109** in method **100** includes computing instantaneous amplitude ratio of two chirp signals using the following equations.

$$A_R(t) = \frac{I_{out}^1(t)}{A_{in} \cos(\phi(t) + \phi_{1,0} + \psi(t))} \text{-----}(4)$$

where,

$A_R(t)$ represents instantaneous amplitude ratio,

$\psi(t)$ represents instantaneous phase shift,

$\phi(t)$ represents instantaneous phase angle of the input dual chirp signals 1 and 2,

$\phi_{1,0}$ represents initial phase angle for the input chirp signal 1,

A_{in} represents amplitude of chirp signals, and

$I_{out}^1(t)$ represents output current response of signal 1.

[0055] In various embodiments, the step **109** in method **100** includes computing instantaneous amplitude ratio of three chirp signals using the following equations.

$$A_R(t) = \frac{A_{out}(t)}{A_{in}} \text{-----}(5)$$

where,

$A_R(t)$ represents instantaneous amplitude ratio,

$A_{out}(t)$ represents instantaneous output amplitude,

$\psi(t)$ represents instantaneous phase shift,

$\phi_{1,0}$ represents phase angle of signal 1,

$\phi_{3,0}$ represents phase angle of signal 3, and

$$A_{out}(t) = \frac{V_{out}^1(t) - V_{out}^3(t)}{(\cos(\phi + \phi_{1,0} + \psi)) - (\cos(\phi + \phi_{3,0} + \psi))} \text{-----}(6)$$

[0056] In various embodiments where a voltage response is acquired for a current input signal, the step **110** in method **100** includes calculating impedance of the system using the following equation for two or more chirp signals.

$$Z = A_R(t) * \exp(i\psi(t)) \text{-----}(7)$$

where,

Z represents unknown impedance,

$A_R(t)$ represents instantaneous amplitude ratio, and

$\Psi(t)$ represents instantaneous phase shift,

[0057] In various embodiments where a current response is acquired for a voltage input signal, the step **110** in method **100** includes calculating impedance of the system using the following equation for two or more chirp signals.

$$Z = \frac{1}{A_R(t)} \exp(-i\Psi(t)) \text{-----}(8)$$

where,

Z represents unknown impedance,

$A_R(t)$ represents instantaneous amplitude ratio, and

$\Psi(t)$ represents instantaneous phase shift.

[0058] In various embodiments where a voltage response is acquired for a voltage input signal, the step **110** in method **100** includes calculating impedance of the system using the following equation for two or more chirp signals.

$$Z = A_R(t) \frac{\exp(i\Psi(t))}{1 - A_R \exp(i\Psi(t))} R_s \text{-----}(9)$$

where,

Z represents unknown impedance,

$A_R(t)$ represents instantaneous amplitude ratio,

$\Psi(t)$ represents instantaneous phase shift, and

R_s represents series resistance with the system under test.

[0059] In one embodiment, the impedance spectra of any system are obtained within 3 to 7s. In one embodiment, the system under test is a linear system and dual chirp signals are used to measure the impedance. In another embodiment, the system under test is a non-linear system and triple chirp signals are used to measure the impedance.

EXAMPLES**[0060] Example 1: Derivation for computation of impedance**

[0061] Chirp analysis technique is performed by considering voltage or current signals for perturbation and response output. The below examples illustrates the perturbation and response for dual chirp and triple chirp signals.

[0062] Example 1A: Using dual phase shifted chirp analysis – Current input, Voltage output

[0063] The dual phase shifted chirp analysis method uses two identical chirp signals which have a predetermined phase shift between them for analysis. In order to compute impedance the two parameters amplitude and phase has to be calculated. There are two expressions and two unknowns, thus allowing for a unique solution to exist without the need for approximation in dual phase shifted chirp analysis method. The additional information made available through the second phase shifted signal eliminates the need for approximation. For dual phase shifted chirp analysis, the system under test is perturbed with two chirp current signals given by (1) and (2).

$$I_1(t) = A_{in} \cos(\emptyset(t) + \emptyset_{1,0}) \text{-----}(1)$$

$$I_2(t) = A_{in} \cos(\emptyset(t) + \emptyset_{2,0}) \text{-----}(2)$$

where,

$\emptyset_{1,0}$ and $\emptyset_{2,0}$ are the known initial phase angles for the two chirp input signals respectively. A_{in} is the amplitude and $\Psi(t)$ is the instantaneous phase angle of the input chirp signals. The voltage response from the system can be modeled as in equation (3) and (4)

$$V_1(t) = A_{out}(t) * \cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t)) \text{-----}(3)$$

$$V_2(t) = A_{out}(t) * \cos(\emptyset(t) + \emptyset_{2,0} + \Psi(t)) \text{-----}(4)$$

where, A_{out} is the amplitude of the output chirp signal. $\Psi(t)$ gives the instantaneous phase shift between the input and the output signal. Dividing (3) by (4),

$$\frac{V_1(t)}{V_2(t)} = \frac{\cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t))}{\cos(\emptyset(t) + \emptyset_{2,0} + \Psi(t))} = k(t) \text{ (say)} \text{-----}(5)$$

[0064] On simplifying equation (5), equation (6) is obtained.

$$\tan(\phi(t) + \Psi(t)) = \frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \text{-----}(6)$$

The instantaneous phase shift $\Psi(t)$ can then be found using equation (7).

$$\Psi(t) = \tan^{-1} \left(\frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \right) - \phi(t) \text{-----}(7)$$

wherein,

$\Psi(t)$ represents phase shift,

$\phi_{1,0}$ and $\phi_{2,0}$ represent initial phase angle for the input dual chirp signals

1 and 2 respectively,

$\phi(t)$ represents instantaneous phase angle of the input dual chirp signals 1 and 2, and

$k(t)$ represents the ratio of output signal 1 to output signal 2.

The amplitude ratio, A_R can now be calculated using equation (8)

$$A_R(t) = \frac{V_1(t)}{A_{in} \cos(\phi(t) + \phi_{1,0} + \Psi(t))} \text{-----}(8)$$

The impedance (Z) is finally evaluated using the expression given in equation (9).

$$Z = A_R(t) \exp(i\Psi(t)) \text{-----}(9)$$

[0065] It is assumed the response of a system when perturbed with a chirp input signal will also be a chirp signal, but shifted in phase and having different amplitude. The amplitude and phase shift will be functions of time.

[0066] Example 1B: Using dual phase shifted chirp analysis – Voltage input, Current output

[0067] The dual phase shifted chirp analysis using voltage input and current output considers the system under test to be perturbed with two chirp voltage signals given by (10) and (11).

$$V_1(t) = A_{in} \cos(\phi(t) + \phi_{1,0}) \text{-----}(10)$$

$$V_2(t) = A_{in} \cos(\phi(t) + \phi_{2,0}) \text{-----}(11)$$

where

$\phi_{1,0}$ and $\phi_{2,0}$ are the known initial phase angles for the two chirp input signals respectively. A_{in} is the amplitude and $\Psi(t)$ is the instantaneous phase angle of the

input chirp signals. The current response from the system can be modeled as in equation (12) and (13)

$$I_1(t) = A_{out}(t) * \cos(\phi(t) + \phi_{1,0} + \Psi(t)) \text{-----}(12)$$

$$I_2(t) = A_{out}(t) * \cos(\phi(t) + \phi_{2,0} + \Psi(t)) \text{-----}(13)$$

where A_{out} is the amplitude of the output chirp signal. $\Psi(t)$ gives the instantaneous phase shift between the input and the output signal. Dividing (13) by (12),

$$\frac{I_2(t)}{I_1(t)} = \frac{\cos(\phi(t) + \phi_{2,0} + \Psi(t))}{\cos(\phi(t) + \phi_{1,0} + \Psi(t))} = k(t) \text{ (say)} \text{-----}(14)$$

[0068] On simplifying equation (14), equation (15) is obtained.

$$\tan(\phi(t) + \Psi(t)) = \frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \text{-----}(15)$$

The instantaneous phase shift $\Psi(t)$ can then be found using equation (16).

$$\Psi(t) = \tan^{-1} \left(\frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \right) - \phi(t) \text{-----}(16)$$

The amplitude ratio, A_R can now be calculated using equation (17)

$$A_R(t) = \frac{I_1(t)}{A_{in} \cos(\phi(t) + \phi_{1,0} + \Psi(t))} \text{-----}(17)$$

The impedance (Z) is finally evaluated using the expression given in equation (18).

$$Z = \frac{1}{A_R(t)} \exp(-i\Psi(t)) \text{-----}(18)$$

[0069] It is assumed the response of a system when perturbed with a chirp input signal will also be a chirp signal, but shifted in phase and having different amplitude. The amplitude and phase shift will be functions of time.

[0070] **Example 1C: Using modified dual phase shifted chirp analysis – Voltage input, Voltage output**

[0071] The modified dual chirp technique is used to evaluate impedance purely based on voltage signals. The modification was based on the voltage division rule, which states that voltage applied across a series combination of impedance, splits in proportion to their individual impedance values. In the modified approach, the chirp signal is applied across a series combination of a resistor, R_s and the system under test (Z) as shown in

FIG.2A. The applied voltage splits across the two elements in proportion to their respective impedance values. Subsequently the voltage response across the system is measured and is used to identify the unknown impedance Z. Equations (19), (20) and (21) illustrate the voltage division rule when applied to the circuit shown in FIG. 2B.

$$V_{in} = V_R + V_Z \text{-----(19)}$$

$$V_R = \frac{V_{in} R_s}{R_s + Z} \text{-----(20)}$$

$$V_Z = \frac{V_{in} Z}{R_s + Z} \text{-----(21)}$$

$$Z = R_s \left(\frac{V_{in}}{V_R} - 1 \right)$$

[0072] Subsequently the voltage response across the system is measured. The perturbation signal applied to the series combination of the test circuit and the series resistor, R_s , is given by equations (22) and (23).

$$V_{in}^1(t) = A_{in} \cos(\phi(t) + \phi_{1,0}) \text{-----(22)}$$

$$V_{in}^2(t) = A_{in} \cos(\phi(t) + \phi_{2,0}) \text{-----(23)}$$

where, $\phi_{1,0}$ and $\phi_{2,0}$ are the initial phase angles for the two chirp input signals respectively, which are predetermined. A_{in} is the amplitude and $\phi(t)$ is the instantaneous phase angle of the input chirp signals.

[0073] It is assumed that a set of impedance elements when connected in series with a known resistance and perturbed with a chirp voltage input as given in equations (22) and (23), produces a chirp voltage response whose amplitude and phase shift are functions of time.

[0074] Based on aforementioned assumption, the voltage response across the system under test (Z) will be of a form given by equations (24) and (25).

$$V_{out}^1(t) = A_{out}(t) * \cos(\phi(t) + \phi_{1,0} + \Psi(t)) \text{-----(24)}$$

$$V_{out}^2(t) = A_{out}(t) * \cos(\phi(t) + \phi_{2,0} + \Psi(t)) \text{-----(25)}$$

[0075] On dividing equation (24) by (25) and simplifying, the instantaneous phase shift ($\Psi(t)$) is obtained as given in equation (26).

$$\Psi(t) = \tan^{-1} \left(\frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \right) - \phi(t) \text{-----(26)}$$

where,

$$k(t) = \frac{V_{out}^1(t)}{V_{out}^2(t)}$$

[0076] The amplitude ratio, A_R is then determined using equation (27).

$$A_R(t) = \frac{V_{out}^1(t)}{A_{in} \cos(\phi(t) + \phi_{1,0} + \psi(t))} \text{-----(27)}$$

[0077] In general, the instantaneous amplitude ratio for output voltage or current response signal is given as,

$$A_R(t) = \frac{S_{out}^1(t)}{A_{in} \cos(\phi(t) + \phi_{1,0} + \psi(t))}$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio,

$\psi(t)$ represents instantaneous phase shift,

$\phi(t)$ represents instantaneous phase angle of the input dual chirp signals 1 and 2,

$\phi_{1,0}$ represents initial phase angle for the input chirp signal 1,

A_{in} represents amplitude of chirp signals, and

$S_{out}^1(t)$ represents the output voltage response of signal 1, $V_{out}^1(t)$ or output current response of signal 1, $I_{out}^1(t)$.

[0078] By using the voltage division, the impedance Z of the system under test can be determined using equation (28).

$$Z = A_R(t) \frac{\exp(i\psi(t))}{1 - A_R \exp(i\psi(t))} R_s \text{-----(28)}$$

where, R_s is the value of the resistor connected in series with the unknown impedance, Z , of the system under test.

[0079] **Example 1D: Using modified dual phase shifted chirp analysis – Current input, Current output**

[0080] The modified dual chirp technique – current input, current output is used to evaluate impedance purely based on current signals. The modification is based on the current division rule, which states that current through a parallel combination of impedance, splits in proportion to their individual impedance values. In the modified

approach, the chirp signal is applied across a parallel combination of a resistor, R_p , the value of which is predetermined and the system under test (Z) as shown in FIG.2B. The applied current splits across the two elements in proportion to their respective impedance values. Subsequently the current response through the system is measured and is used to identify the unknown impedance Z . Equations (29), (30) and (31) illustrate the current division rule when applied to the circuit shown in FIG. 2B.

$$I_{in} = I_R + I_Z \text{-----} (29)$$

$$I_R R_p = I_Z Z \text{-----} (30)$$

$$I_Z = \frac{I_{in} R_p}{R_p + Z} \text{-----} (31)$$

And the impedance of the system Z , is then computed as shown in Equation (32):

$$Z = R_p \left(\frac{I_{in}}{I_Z} - 1 \right) \text{-----} (32)$$

The perturbation currents are as follows

$$I_{in}^1(t) = A_{in} * \cos(\phi(t) + \phi_{1,0}) \text{-----} (33)$$

$$I_{in}^2(t) = A_{in} * \cos(\phi(t) + \phi_{2,0}) \text{-----} (34)$$

The response for the above perturbation would be:

$$I_{out}^1(t) = A_{out}(t) * \cos(\phi(t) + \phi_{1,0} + \psi(t)) \text{-----} (35)$$

$$I_{out}^2(t) = A_{out}(t) * \cos(\phi(t) + \phi_{2,0} + \psi(t)) \text{-----} (36)$$

Phase shift would be given as:

$$\psi(t) = \tan^{-1} \left(\frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \right) - \phi(t) \text{-----} (37)$$

Where:

$$k(t) = \frac{I_{out}^1(t)}{I_{out}^2(t)}$$

The instantaneous amplitude ratio is then given as:

$$A_R(t) = \frac{I_{out}^1(t)}{A_{in} * \cos(\phi(t) + \phi_{1,0} + \psi(t))} \text{-----} (38)$$

Based on current division rule, the impedance of the system under test is determined by the equation (39)

$$Z = R_p \left[\frac{1}{A_R(t)} \exp(-i\psi(t)) - 1 \right] \text{-----} (39)$$

[0081] Example 2: Derivation for computation of impedance using triple phase shifted chirp analysis

[0082] Example 2A: Voltage input, Voltage output

[0083] Triple phase shifted chirp analysis (or triple chirp analysis) is a method that estimates impedance information of a system based on its response to three input chirp signals, which are phase shifted by a known angle. In addition, all three signals have a predefined DC shift.

[0084] Suppose an input chirp voltage signal be applied across the overall system (series combination of a resistor R_s and load L as shown in FIG. 2A), the voltage response across the load L is modeled as a chirp signal with an amplitude ratio, phase shift and a mean shift that are functions of time (and frequency) akin to modified dual chirp analysis.

[0085] Three input signals with different initial phases and predefined phase shift, equations (40), (41), (42) are applied across the overall system.

$$V_{in}^1(t) = A_{tm,in} + A_{in} \cos(\emptyset(t) + \emptyset_{1,0}) \text{-----}(40)$$

$$V_{in}^2(t) = A_{tm,in} + A_{in} \cos(\emptyset(t) + \emptyset_{2,0}) \text{-----}(41)$$

$$V_{in}^3(t) = A_{tm,in} + A_{in} \cos(\emptyset(t) + \emptyset_{3,0}) \text{-----}(42)$$

[0086] $\emptyset_{1,0}$, $\emptyset_{2,0}$ and $\emptyset_{3,0}$ are initial phase angles of three input signals and $A_{tm,in}$ is the time varying DC shift of the input signals. Corresponding output voltages are modeled as equations (43),(44),(45)

$$V_{out}^1(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t)) \text{-----}(43)$$

$$V_{out}^2(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{2,0} + \Psi(t)) \text{-----}(44)$$

$$V_{out}^3(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----}(45)$$

where, $A_{tm,out}(t)$ is the mean (instantaneous DC shift) of output signal at any instant t and is assumed a function of time to be able to handle output signals with varying mean or non-stationary signals. $A_{tm,out}(t)$ is the trend in the system's response. Three equations corresponding to three input-output data are used to derive analytical expressions for the unknowns (mean, amplitude and phase shift) as a function of time.

[0087] On subtracting equation(45) from equations (43) and (44),

$$V_{out}^1(t) - V_{out}^3(t) = A_{out}(t) * (\cos(\emptyset + \emptyset_{1,0} + \Psi) - \cos(\emptyset + \emptyset_{3,0} + \Psi)) \text{-----}(46)$$

$$V_{out}^2(t) - V_{out}^3(t) = A_{out}(t) * (\cos(\emptyset + \emptyset_{2,0} + \Psi) - \cos(\emptyset + \emptyset_{3,0} + \Psi)) \text{-----}(47)$$

[0088] Dividing equation (46) by (47), we get equation(48),

$$\frac{V_{out}^1(t) - V_{out}^3(t)}{V_{out}^2(t) - V_{out}^3(t)} = \frac{(\cos(\emptyset + \emptyset_{1,0} + \Psi) - \cos(\emptyset + \emptyset_{3,0} + \Psi))}{(\cos(\emptyset + \emptyset_{2,0} + \Psi) - \cos(\emptyset + \emptyset_{3,0} + \Psi))} = k(t)(say) \text{-----}(48)$$

[0089] Analytical expression for instantaneous phase shift can be obtained by simplifying equation (48) and instantaneous amplitude ratio can be obtained from equation (46). $A_{tm,out}$ can be estimated using (45). The final expressions are as follows:

$$\Psi(t) = \tan^{-1} \left(\frac{k(t)(\cos(\emptyset_{2,0}) - \cos(\emptyset_{3,0})) + (\cos(\emptyset_{3,0}) - \cos(\emptyset_{1,0}))}{k(t)(\sin(\emptyset_{2,0}) - \sin(\emptyset_{3,0})) + (\sin(\emptyset_{3,0}) - \sin(\emptyset_{1,0}))} \right) - \emptyset(t) \text{-----}(49)$$

wherein,

$\Psi(t)$ represents instantaneous phase shift,

$\emptyset(t)$ represents instantaneous phase angle of the input triple chirp signals
1, 2 and 3,

$\emptyset_{1,0}$ represents initial phase angle for the input chirp signal 1,

$\emptyset_{2,0}$ represents initial phase angle for the input chirp signal 2, and

$\emptyset_{3,0}$ represents initial phase angle for the input chirp signal 3.

$$A_{out}(t) = \frac{V_{out}^1(t) - V_{out}^3(t)}{(\cos(\emptyset + \emptyset_{1,0} + \Psi) - \cos(\emptyset + \emptyset_{3,0} + \Psi))} \text{-----}(50)$$

$$A_{tm,out}(t) = V_{out}^3(t) - A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----}(51)$$

[0090] Impedance (Z) of the system can be evaluated from instantaneous amplitude ratio ($A_R = A_{out}/A_{in}$) and instantaneous phase shift ($\Psi(t)$) using (43).

$$Z = A_R(t) \frac{\exp(i\Psi(t))}{1 - A_R(t) * \exp(i\Psi(t))} R_s \text{-----}(52)$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio,

$\Psi(t)$ represents instantaneous phase shift, and

R_s represents a known resistance in series with the system under test.

[0091] **Example 2B: Voltage input, Current output**

[0092] The perturbation voltage signals are as follows:

$$V_{in}^1(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{1,0}) \text{-----}(53)$$

$$V_{in}^2(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{2,0}) \text{-----}(54)$$

$$V_{in}^3(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{3,0}) \text{-----}(55)$$

The response current signals are as follows:

$$I_{out}^1(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t)) \text{-----}(56)$$

$$I_{out}^2(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{2,0} + \Psi(t)) \text{-----}(57)$$

$$I_{out}^3(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----}(58)$$

Through similar algebraic manipulations as shown in the previous case the final expressions for instantaneous phase shift $\Psi(t)$, instantaneous amplitude ratio $A_R(t)$, instantaneous DC Shift $A_{tm,out}(t)$, and the impedance of the system Z, are:

$$\Psi(t) = \tan^{-1} \left(\frac{k(t) * (\cos(\emptyset_{2,0}) - \cos(\emptyset_{3,0})) + (\cos(\emptyset_{3,0}) - \cos(\emptyset_{1,0}))}{k(t) * (\sin(\emptyset_{2,0}) - \sin(\emptyset_{3,0})) + (\sin(\emptyset_{3,0}) - \sin(\emptyset_{1,0}))} \right) - \emptyset(t) \text{-----}(59)$$

Where:

$$k(t) = \frac{I_{out}^1(t) - I_{out}^3(t)}{I_{out}^2(t) - I_{out}^3(t)}$$

Where,

$I_{out}^1(t)$ represents the current response of signal 1,

$I_{out}^2(t)$ represents the current response of signal 2, and

$I_{out}^3(t)$ represents the current response of signal 3.

$$A_R(t) = \frac{A_{out}(t)}{A_{in}} \text{-----}(60)$$

Where:

$$A_{out}(t) = \frac{I_{out}^1(t) - I_{out}^3(t)}{(\cos(\emptyset(t) + \emptyset_{1,0} + \Psi) - \cos(\emptyset(t) + \emptyset_{3,0} + \Psi))}$$

$$A_{tm,out}(t) = I_{out}^3 - A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----}(61)$$

$$Z = \frac{1}{A_R(t)} \exp(-i\psi(t)) \text{-----}(62)$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio, and

$\Psi(t)$ represents instantaneous phase shift.

[0093] Example 2C: Current input, Voltage output

[0094] The perturbation current signals are as follows:

$$I_{in}^1(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{1,0}) \text{-----} (63)$$

$$I_{in}^2(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{2,0}) \text{-----} (64)$$

$$I_{in}^3(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{3,0}) \text{-----} (65)$$

The response voltage signals are as follows:

$$V_{out}^1(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t)) \text{-----} (66)$$

$$V_{out}^2(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{2,0} + \Psi(t)) \text{-----} (67)$$

$$V_{out}^3(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----} (68)$$

$$\Psi(t) = \tan^{-1} \left(\frac{k(t) * (\cos(\emptyset_{2,0}) - \cos(\emptyset_{3,0})) + (\cos(\emptyset_{3,0}) - \cos(\emptyset_{1,0}))}{k(t) * (\sin(\emptyset_{2,0}) - \sin(\emptyset_{3,0})) + (\sin(\emptyset_{3,0}) - \sin(\emptyset_{1,0}))} \right) - \emptyset(t) \text{-----} (69)$$

$$k(t) = \frac{V_{out}^1(t) - V_{out}^3(t)}{V_{out}^2(t) - V_{out}^3(t)}$$

Where,

$V_{out}^1(t)$ represents the voltage response of signal 1,

$V(t)$ represents the voltage response of signal 2, and

$V_{out}^3(t)$ represents the voltage response of signal 3.

$$A_R(t) = \frac{A_{out}(t)}{A_{in}} \text{-----} (70)$$

Where,

$A_R(t)$ represents instantaneous amplitude ratio,

$A_{out}(t)$ represents instantaneous output amplitude,

$\Psi(t)$ represents instantaneous phase shift,

$\emptyset_{1,0}$ represents phase angle of signal 1, and

$\emptyset_{3,0}$ represents phase angle of signal 3,

$$A_{out}(t) = \frac{V_{out}^1(t) - V_{out}^3(t)}{(\cos(\emptyset(t) + \emptyset_{1,0} + \Psi) - \cos(\emptyset(t) + \emptyset_{3,0} + \Psi))}$$

$$A_{tm,out}(t) = V_{out}^3 - A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----}(71)$$

$$Z = A_R(t) \exp(i\psi(t)) \text{-----}(72)$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio, and

$\Psi(t)$ represents instantaneous phase shift.

[0095] Example 2D: Current input, Current output

[0096] The perturbation current signals are as follows:

$$I_{in}^1(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{1,0}) \text{-----}(73)$$

$$I_{in}^2(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{2,0}) \text{-----}(74)$$

$$I_{in}^3(t) = A_{tm,in} + A_{in} * \cos(\emptyset(t) + \emptyset_{3,0}) \text{-----}(75)$$

The response voltage signals are as follows:

$$I_{out}^1(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t)) \text{-----}(76)$$

$$I(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{2,0} + \Psi(t)) \text{-----}(77)$$

$$I_{out}^3(t) = A_{tm,out}(t) + A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----}(78)$$

$$\Psi(t) = \tan^{-1} \left(\frac{k(t) * (\cos(\emptyset_{2,0}) - \cos(\emptyset_{3,0})) + (\cos(\emptyset_{3,0}) - \cos(\emptyset_{1,0}))}{k(t) * (\sin(\emptyset_{2,0}) - \sin(\emptyset_{3,0})) + (\sin(\emptyset_{3,0}) - \sin(\emptyset_{1,0}))} \right) - \emptyset(t) \text{-----}(79)$$

$$k(t) = \frac{I_{out}^1(t) - I_{out}^3(t)}{I_{out}^2(t) - I_{out}^3(t)}$$

$$A_R(t) = \frac{A_{out}(t)}{A_{in}} \text{-----}(80)$$

Where:

$$A_{out}(t) = \frac{I_{out}^1(t) - I_{out}^3(t)}{(\cos(\emptyset(t) + \emptyset_{1,0} + \Psi) - \cos(\emptyset(t) + \emptyset_{3,0} + \Psi))}$$

$$A_{tm,out}(t) = I_{out}^3 - A_{out}(t) * \cos(\emptyset(t) + \emptyset_{3,0} + \Psi(t)) \text{-----}(81)$$

$$Z = R_p \left[\frac{1}{A_R(t)} \exp(-i\psi(t)) - 1 \right] \text{-----}(82)$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio,

$\Psi(t)$ represents instantaneous phase shift, and

R_p represents a known resistance in parallel with the system under test.

[0097] Example 3: Validation of the dual phase shifted chirp analysis method**[0098] Example 3A: Development of equivalent models to validate impedance measurement results**

[0099] In order to validate impedance measurement results for various kinds of electrochemical systems, equivalent circuit models have been developed. In these models, various arrangements of passive circuit elements are used to simulate various attributes of electrochemical systems. The master circuit from which the equivalent test circuits are derived by setting suitable values for each element is shown in FIG. 3. Three equivalent test circuits are considered for validation. The values for the circuit components are given in Table 1. Circuit 1 represents a simple Randles circuit while circuit 2 represents an electrochemical reaction with adsorbed intermediates. Circuit 3 incorporates an RL element. The circuit values were chosen to obtain visually distinct features in the impedance profile.

Table 1: Values for Components in the Master Circuit

Circuit Number	R1 (Ω)	R2 (Ω)	C1 (μF)	R3 (Ω)	R4 (Ω)	C2 (μF)	C3 (μF)	R5 (Ω)	R6 (Ω)	L1 (H)
1	981	987	10	Short	Short	Open	Open	Open	Open	Open
2	497	Short	Open	976	1965	10	1	Short	Short	Open
3	1000	1000	1	1000	Short	Open	47	1000	0.6	0.0987

[0100] Example 3B: In-silico validation of dual phase shifted chirp analysis method

[0101] The dual phase shifted chirp analysis method was validated through simulations in MATLAB/Simulink environment. MATLAB/Simulink was used for simulating chirp signals on a given test circuit and acquire the response. The signal parameters are mentioned in the Table 2.

Table 2: Input Signal Parameters for Dual Chirp Analysis

Parameter	Value
------------------	--------------

	Signal 1	Signal2
Signal Type	Current	Current
Chirp Type	Exponential	Exponential
Frequency Range	0.1Hz to 10 kHz	0.1Hz to 10 kHz
Amplitude(Peak to peak)	200 μ A	200 μ A
Initial Phase	0 Radians	Pi/6 Radians
Signal duration	2 seconds	2 seconds

[0102] The Simulink block diagram for dual chirp analysis is shown in FIG. 4. Dual chirp input current signals, whose parameters are specified in the 'Chirp' block, are applied through a controlled current source to the test circuit (depicted as 'Load') and the voltage response across it is measured. 'Load (L)' is replaced with the corresponding equivalent circuit to be tested. This data is subsequently analyzed using the dual phase shifted chirp analysis algorithm. The results from the analysis are compared with the theoretical 'Impedance Measurement' block. The impedance profiles obtained from dual chirp analysis method against the theoretical impedance for the test circuits circuit 1, circuit 2 and circuit 3 with parameters given in Table 1 generated from the master circuit are compared with impedance profiles obtained from dual chirp method as shown in FIG. 5A, FIG. 5B and FIG. 5C respectively. It can be observed that the impedance profiles obtained from dual chirp method matches with the theoretical impedance validating the method.

[0103] Example 3C: Experimental validation of dual phase shifted chirp analysis method

[0104] The experimental setup includes a 'USB 1616HS - 4' DataAcquisition (DAQ) Card from Measurement and Computing, a voltage controlled current source (VCCS) based on the LM741 operational amplifier and a solderless breadboard with the test circuits on it. The given DAQ generates voltage signals and hence a VCCS is used to convert the voltage signal to an equivalent current signal.

[0105] FIG.6A shows the block diagram of the hardware setup for dual chirp analysis. The DAQ is connected to a computer. The DAQ is used for applying the chirp signal to the test circuit and receive the response. Depending on the parameters chosen, data for the dual chirp signal is generated in the computer as a sequence of numerical values. The DAQ device is controlled using the Data Acquisition Toolbox in MATLAB. The DAQ card receives the chirp sequence and converts it into a continuous voltage chirp signal. This continuous voltage signal is applied to the VCCS circuit through the DAQ's analog output pin. The VCCS converts the voltage signal to an equivalent current signal. The output current of the VCCS is limited to a few micro amperes. This current signal is applied to the test circuit. The voltage response from the circuit is measured through the analog input pin at the DAQ. The DAQ then converts the voltage response from the circuit to a set of discrete voltage values and returns it to the computer. The response from the DAQ is then filtered and analyzed in the computer using the dual chirp algorithm. The voltage response is shown in FIG .6B.

[0106] Example 4:Validation of modified dual phase shifted chirp analysis method

[0107] The modified dual phase shifted chirp analysis method was validated through both simulations in MATLAB and experiments on passive circuit elements. The passive circuits shown in FIG. 3 with values of the components mentioned in Table 1 were used to validate the modified dual phase chirp analysis method. The signal parameters for the modified dual chirp method are mentioned in Table 3.

Table 3: Input Signal Parameters for Modified Dual Chirp Analysis

Parameter	Value	
	Signal 1	Signal 2
Signal Type	Voltage	Voltage
Chirp Type	Exponential	Exponential
Frequency Range	0.1Hz to 10 kHz	0.1Hz to 10 kHz

Amplitude(Peak to peak)	2V	2V
Initial Phase	0 Radians	Pi/6 Radians
Signal duration	2 seconds	2 seconds

[0108] Example 4A: Validation of modified dual phase shifted chirp analysis method using simulation

[0109] The modified method was validated through simulations performed in MATLAB/Simulink. The block diagram used for the simulation is as shown in FIG.7. The 'Chirp' block, controls a 'controlled voltage source'. Dual chirp voltage signals as defined in Table 3 are applied to the combination of the series resistor (R_s) and the circuit under test, depicted by the 'load' block. 'Load' is replaced with the corresponding circuit to be tested. The voltage response across the circuit is measured and is used for further analysis.

[0110] Once the data is collected, it is analyzed using the modified dual chirp algorithm. FIG. 8 shows the algorithm for in-silico implementation of modified dual chirp analysis. The simulated results from the modified dual chirp method are compared with those from dual chirp technique and the theoretical impedance in FIG. 9A, FIG. 9B and FIG. 9C. It can be observed that the results from the modified dual chirp algorithm are closer to the theoretical impedance profile validating the algorithm.

[0111] Example 4B: Experimental validation of modified dual chirp analysis

[0112] A. Tolerance to down sampling.

[0113] Initially the number of samples is downsized and the number of data points is reduced to depict the chirp signal, so that less memory or storage is used on the device. The total number of samples required to represent the complete signal is given by the following equation.

$$\text{Number of samples} = T \times \text{sample rate} \text{-----}(1)$$

where, T represents the duration of the chirp signal, while sample rate is the number of samples per second. Nyquist sampling theorem dictates the minimum sampling rate of the signal to be greater than at least twice the natural frequency. The impedance profiles

were studied under various sample rates viz., 15,000 S/s, 20,000 S/s, 40,000 S/s and 50,000 S/s. It was found that all the sample rates were able to capture the low frequency regime of the impedance profile in its entirety. Based on the analysis, a sampling rate of 40,000 S/s was deemed to be a reasonable sample rate for practical purposes and hence this sampling rate was chosen for the experimental validation.

[0114] Modified dual phase shifted chirp analysis was experimentally verified by the schematic of experimental setup as shown in FIG.10. The chirp voltage signal from the analog output pin on the DAQ is applied to a series combination of ' R_s ' and the test circuit. The chirp voltage response is measured across the test circuit.

[0115] The voltage response across the test circuit is then measured at the analog input pin on the DAQ card. The response signal is filtered and analyzed using the modified dual phase shifted chirp algorithm. FIG. 11A, FIG.11B and FIG. 11C compares the results for modified dual chirp analysis obtained through hardware setup against theoretical impedance and simulations performed on the respective circuits. Experimental results obtained using modified dual chirp analysis method using voltage signals shows a close match with theoretical impedance and simulated results.

[0116] Example 5: Comparison of dual chirp analysis method with conventional EIS method

[0117] Dual chirp technique makes use of transient information unlike EIS that requires the transients to die down before the measurements are taken. Considering a frequency range of 0.1Hz to 10 KHz at 5 points per decade and a minimum of 2 cycles at each frequency, the signal duration itself for a conventional single-sine EIS experiment would be around 45.4 seconds. However, this does not include the time between each frequency step during which the system is allowed to reach steady state, one of the fundamental requirements in conventional EIS. Increasing the number of frequency points within a given range may further increase the signal duration, especially when considering lower frequencies. However, impedance estimation through dual chirp technique, over the same frequency range, takes less than 5 seconds in entirety. The total

duration for the both the signals is 4 seconds and it takes less than 1 second on an average to process about 160,000 samples and compute the impedance. Thus dual chirp technique is almost 10 times faster than conventional EIS.

[0118] Moreover, the proposed technique sweeps continuously over the entire frequency range unlike conventional EIS which computes impedance only at a discrete set of frequencies. This feature enables dual chirp technique to gather more information about the system, without an increase in signal duration. When a constant DC shift exists, dual chirp algorithm may use a correction factor before analysis to negate the DC shift. The DC shift to be subtracted from the response can be computed as given in the following equations.

$$DC \text{ shift of signal } x', DC_x = \frac{\max(x) + \min(x)}{2} \text{-----}(2)$$

[0119] Example 6: In-silico validation of Triple phase shifted chirp analysis

[0120] Triple phase shifted chirp analysis is validated by estimating impedance using the data collected from various test circuits emulated in MATLAB/Simulink and comparing with the theoretical impedance for the corresponding circuits. For generating data, a Simulink model as shown in FIG. 12 is used. Parameters of three input signals used for simulations are provided in Table 4. Input data generated from the chirp block is added with a constant DC shift and then applied across the series combination of resistor (R_s) and load. The output voltage across the load is then measured and is used for impedance estimation using triple chirp algorithm. DC shift ($A_{tm,out}$) obtained using equation (3) varies with time which is non-intuitive as input has a constant DC shift.

$$A_{tm,out}(t) = V_{out}^3(t) - A_{out}(t) \cos(\phi(t) + \phi_{3,0} + \varphi(t)) \text{-----}(3)$$

where, $\varphi(t)$ represents instantaneous phase shift, $A_{tm,out}(t)$ is trend in system's response, $\phi(t)$ represents phase angle.

[0121] FIG. 13A, FIG. 13B and FIG. 13C shows the properties of impedance and output voltage signal estimated using triple phase shift algorithm which includes variation of DC shift ($A_{tm,out}$) with frequency along with the Bode plots for circuit 3 whose circuit diagram and parameters may be found in FIG. 3 and Table 1 respectively.

[0122] The impedance estimated using triple chirp algorithm for various test circuits are provided in FIG. 14A, FIG. 14B and FIG. 14C. As shown in the FIG. 14A, FIG. 14B and FIG. 14C in comparison to theoretical impedance and the impedance estimated from modified dual chirp analysis using input-output data without any DC shift, it can be observed that the impedance estimated using triple chirp algorithm matches exactly with that obtained from dual chirp analysis. So, in applications requiring high accuracy, triple chirp method may be used.

Table 4: Input Signal Parameters for Triple Chirp Analysis

Parameter	Value		
	Signal 1	Signal 2	Signal 3
Signal Type	Voltage	Voltage	Voltage
Chirp Type	Exponential	Exponential	Exponential
Frequency Range	0.1Hz to 10 kHz	0.1Hz to 10 kHz	0.1Hz to 10 kHz
Amplitude(Peak to peak)	2V	2V	2V
Initial Phase	0 Radians	Pi/20 Radians	Pi/40
Signal duration	2 seconds	2 seconds	2 seconds

[0123] The total time for impedance estimation using triple chirp analysis for a frequency range of 0.1 Hz to 10000 Hz is around 6.5 seconds which means approximately 85% reduction in time is obtained in comparison to conventional EIS technique. The time required by conventional EIS method for impedance estimation is 45.4 seconds as calculated corresponding to 5 frequencies in each decade of frequency while using sinusoidal signals of 2 full cycles for each frequency.

[0124] Example 6A: Experimental validation of triple phase shifted chirp analysis

[0125] Triple phase shifted chirp algorithm is shown in FIG. 15. The impedance obtained for the circuit using triple phase shifted chirp algorithm in comparison to the theoretical impedance is shown in FIG. 16. An additional de-noising level was included

in the circuit. For both amplitude and phase, different intervals of data are identified based on qualitative trend and a best fit polynomial is obtained while ensuring continuity at the boundary.

[0126] Example 7: Implementation of the technique for a wide frequency range of interest

[0127] A frequency range of 0.1 Hz to 10 kHz was chosen for all the analysis carried out using various chirp analysis techniques. When a system's behavior in very low frequency regime is significant, impedance has to be estimated in those frequency ranges. The method was implemented for a frequency range of 0.001Hz to 10kHz and impedance was estimated by either a) increasing the signal duration / time span of the input chirp signal or b) using multiple frequency regimes and combining the results obtained from triple chirp analysis to arrive at a single impedance plot for the whole frequency regime of interest. When the signal was split into low, mid and high frequency regimes, high sampling rates were required only for the high frequency regime and hence comparatively very less amount of data was needed to estimate impedance. This improved the computational time.

WE CLAIM:

1. A method for measuring impedance Z of a system, comprising:
 - a. generating at least one chirp signal for perturbing the system under test;
 - b. perturbing the system under test with at least one perturbation chirp signal, wherein the signal is a voltage or a current signal;
 - c. receiving transient response signals from the system, wherein the response is either a voltage or a current signal;
 - d. processing the received signals to remove quantization errors and external interferences;
 - e. analyzing the response to obtain impedance spectrum, wherein analyzing comprises:
 - assessing the amplitude and phase angle of the system from the response data, wherein assessing comprises:
 - computing instantaneous input amplitude of the chirp signals;
 - computing instantaneous output phase angle of the chirp signals;
 - converting the instantaneous output phase angle to a monotonically increasing function, wherein the function increases from zero to infinity;
 - calculating instantaneous output phase shift of the chirp signals;
 - calculating instantaneous output amplitude of the chirp signals; wherein the instantaneous amplitude ratio is the ratio of instantaneous output amplitude to instantaneous input amplitude; and

calculating impedance of the system, wherein the impedance is a function of the instantaneous amplitude ratio and the instantaneous phase shift.

2. The method of claim 1, wherein the chirp signal is a dual chirp signal or a triple chirp signal.
3. The method of claim 2, wherein the signal is a dual chirp signal and the two signals are separated by predefined phase shifts.
4. The method of claim 2, wherein the signal is a triple chirp signal and the three signals are separated by predefined phase shifts with predefined DC levels.
5. The method of claim 3, wherein the voltage response of the system for a current perturbation or a voltage perturbation determines impedance of the system.
6. The method of claim 3, wherein the current response of the system for a current perturbation or a voltage perturbation determines impedance of the system.
7. The method of claim 4, wherein the voltage response of the system for a current perturbation or a voltage perturbation determines impedance of the system.
8. The method of claim 4, wherein the current response of the system for a voltage perturbation or a current perturbation determines impedance of the system.
9. The method of claim 3, wherein the instantaneous phase shift is calculated using the following relation:

$$\Psi(t) = \tan^{-1} \left(\frac{\cos(\phi_{2,0}) - k(t) * \cos(\phi_{1,0})}{\sin(\phi_{2,0}) - k(t) * \sin(\phi_{1,0})} \right) - \phi(t)$$

wherein,

$\Psi(t)$ represents phase shift,

$\emptyset_{1,0}$ and $\emptyset_{2,0}$ represent initial phase angle for the input dual chirp signals 1 and 2 respectively,

$\emptyset(t)$ represents instantaneous phase angle of the input dual chirp signals 1 and 2, and

$k(t)$ represents the ratio of output signal 1 to output signal 2.

10. The method of claim 3, wherein the instantaneous amplitude ratio is given by:

$$A_R(t) = \frac{S_{out}^1(t)}{A_{in} \cos(\emptyset(t) + \emptyset_{1,0} + \Psi(t))}$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio,

$\Psi(t)$ represents instantaneous phase shift,

$\emptyset(t)$ represents instantaneous phase angle of the input dual chirp signals 1 and 2,

$\emptyset_{1,0}$ represents initial phase angle for the input chirp signal 1,

A_{in} represents amplitude of chirp signals, and

$S_{out}^1(t)$ represents the output voltage response of signal 1, $V_{out}^1(t)$ or output current response of signal 1, $I_{out}^1(t)$.

11. The method of claim 4, wherein the instantaneous phase shift is given by:

$$\Psi(t) = \tan^{-1} \left(\frac{k(t) * (\cos(\emptyset_{2,0}) - \cos(\emptyset_{3,0})) + (\cos(\emptyset_{3,0}) - \cos(\emptyset_{1,0}))}{k(t) * (\sin(\emptyset_{2,0}) - \sin(\emptyset_{3,0})) + \sin((\emptyset_{3,0}) - \sin(\emptyset_{1,0}))} \right) - \emptyset(t)$$

wherein,

$\Psi(t)$ represents instantaneous phase shift,

$\emptyset(t)$ represents instantaneous phase angle of the input triple chirp signals 1, 2 and 3,

$\emptyset_{1,0}$ represents initial phase angle for the input chirp signal 1,

$\emptyset_{2,0}$ represents initial phase angle for the input chirp signal 2, and

$\phi_{3,0}$ represents initial phase angle for the input chirp signal 3.

12. The method of claim 7 or 9, wherein $k(t)$ is given by,

$$k(t) = \frac{V_{out}^1(t) - V_{out}^3(t)}{V_{out}^2(t) - V_{out}^3(t)}$$

$V_{out}^1(t)$ represents the voltage response of signal 1,

$V(t)$ represents the voltage response of signal 2, and

$V_{out}^3(t)$ represents the voltage response of signal 3.

13. The method of claim 8 or 9, wherein $k(t)$ is given by,

$$k(t) = \frac{I_{out}^1(t) - I_{out}^3(t)}{I_{out}^2(t) - I_{out}^3(t)}$$

$I_{out}^1(t)$ represents the current response of signal 1,

$I_{out}^2(t)$ represents the current response of signal 2, and

$I_{out}^3(t)$ represents the current response of signal 3.

14. The method of claim 7, wherein mean of the output signal for instantaneous DC shift is given by,

$$A_{tm,out}(t) = V_{out}^3(t) - A_{out}(t) \cos(\phi_{3,0} + \phi + \psi(t))$$

15. The method of claim 8, wherein mean of the output signal for instantaneous DC shift is given by,

$$A_{tm,out}(t) = I_{out}^3(t) - A_{out}(t) \cos(\phi_{3,0} + \phi + \psi(t))$$

16. The method of claim 1 or 7, wherein the instantaneous amplitude ratio is given by,

$$A_R(t) = \frac{A_{out}(t)}{A_{in}}$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio,

$A_{out}(t)$ represents instantaneous output amplitude,

$\psi(t)$ represents instantaneous phase shift,

$\phi_{1,0}$ represents phase angle of signal 1,

$\phi_{3,0}$ represents phase angle of signal 3, and

$$A_{out}(t) = \frac{V_{out}^1(t) - V_{out}^3(t)}{(\cos(\phi + \phi_{1,0} + \Psi(t))) - (\cos(\phi + \phi_{3,0} + \Psi(t)))}$$

17. The method of claim 1 or 8, wherein the amplitude ratio is given by:

$$A_R(t) = \frac{A_{out}(t)}{A_{in}}$$

wherein,

$A_R(t)$ represents the instantaneous amplitude ratio,

$A_{out}(t)$ represents the instantaneous output amplitude,

$\Psi(t)$ represents instantaneous phase shift,

$\phi_{1,0}$ represents phase angle of signal 1,

$\phi_{3,0}$ represents phase angle of signal 3, and

$$A_{out}(t) = \frac{I_{out}^1(t) - I_{out}^3(t)}{(\cos(\phi + \phi_{1,0} + \Psi(t))) - (\cos(\phi + \phi_{3,0} + \Psi(t)))}$$

18. The method of claim 5 or 7, wherein the impedance Z for current signal perturbation having voltage signal response is given by:

$$Z = A_R(t) \exp(i\Psi(t))$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio, and

$\Psi(t)$ represents instantaneous phase shift.

19. The method of claim 6 or 8, wherein the impedance Z for voltage signal perturbation having current signal response is given by:

$$Z = \frac{1}{A_R(t)} \exp(-i\Psi(t))$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio, and

$\Psi(t)$ represents instantaneous phase shift.

20. The method of claim 5 or 7, wherein, the impedance Z for voltage signal perturbation having voltage signal response is given by:

$$Z = A_R(t) \frac{\exp(i\Psi(t))}{1 - A_R(t) \exp(i\Psi(t))} R_s$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio,

$\Psi(t)$ represents instantaneous phase shift, and

R_s represents a known resistance in series with the system under test.

21. The method of claim 6 or 8, wherein, the impedance Z for current signal perturbation having current signal response is given by:

$$Z = R_p \left[\frac{1}{A_R(t)} \exp(-i\psi(t)) - 1 \right]$$

wherein,

$A_R(t)$ represents instantaneous amplitude ratio,

$\Psi(t)$ represents instantaneous phase shift, and

R_p represents a known resistance in parallel with the system under test.

22. The method of claim 1, wherein processing the received signal comprises denoising the response signals using at least one filters and smoothing the filtered signals.

23. The method of claim 1, wherein time taken to measure the impedance ranges from 3-7 seconds for perturbation signals of frequency ranging from 0.1 Hz to 10 kHz.

24. The method of claim 1, wherein the impedance is measurable for perturbation signals of frequency ranging from 0.001 Hz to 10 kHz.

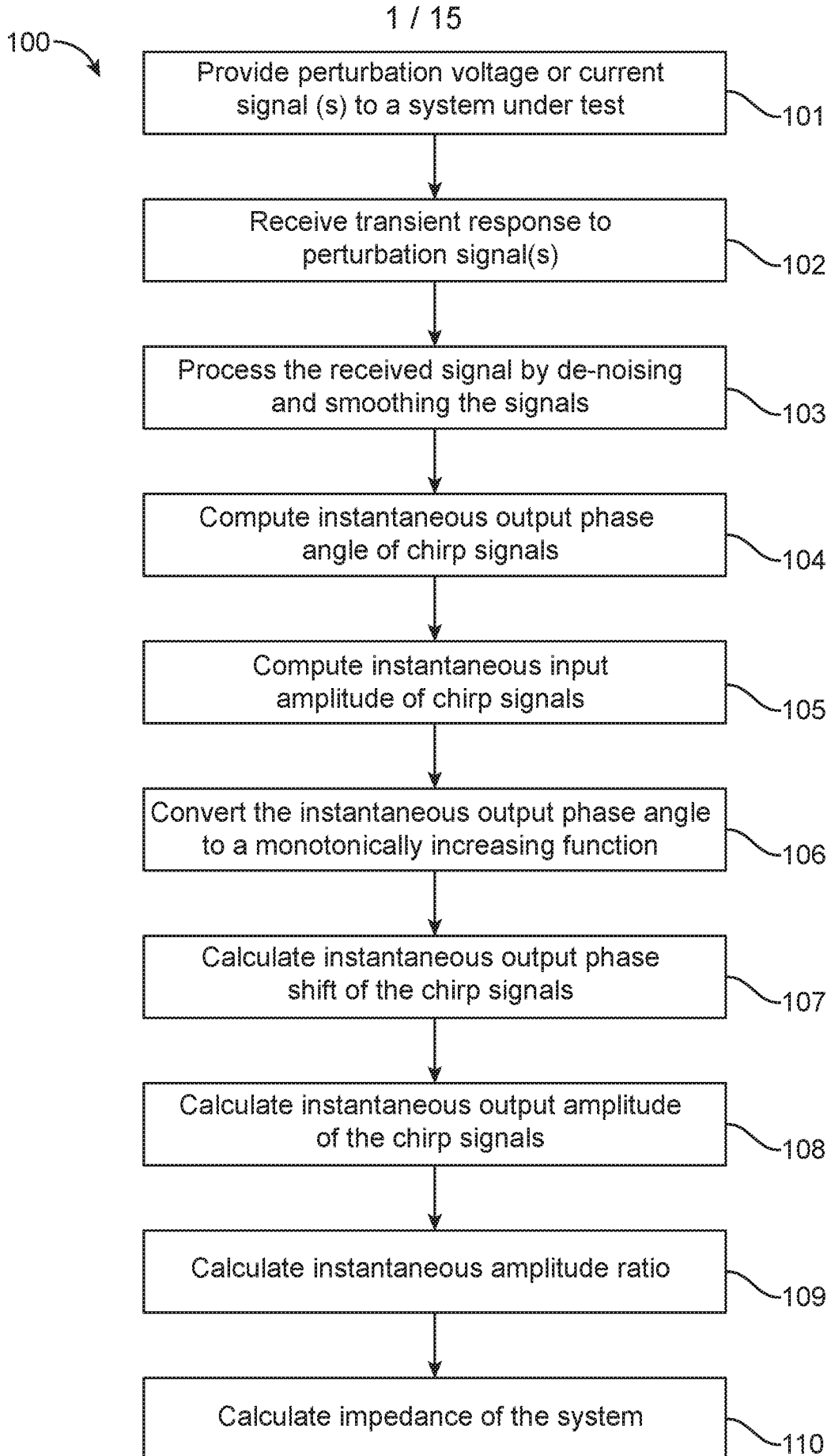


FIG. 1

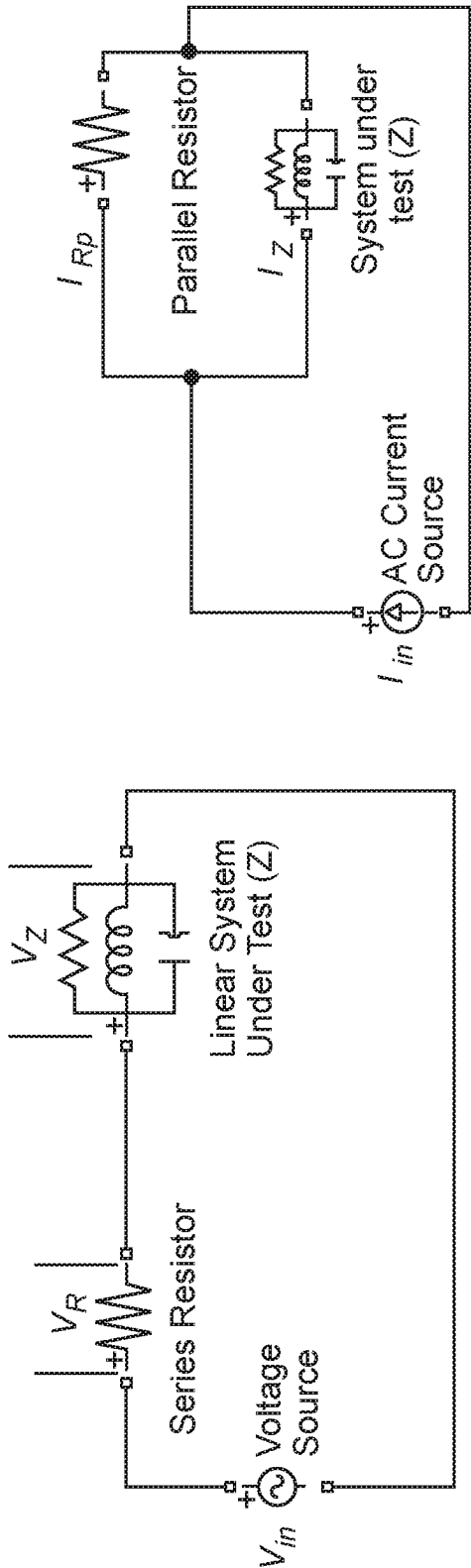


FIG. 2A

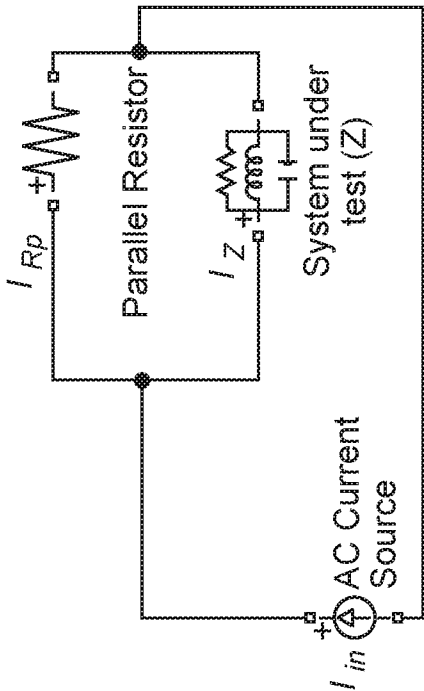


FIG. 2B

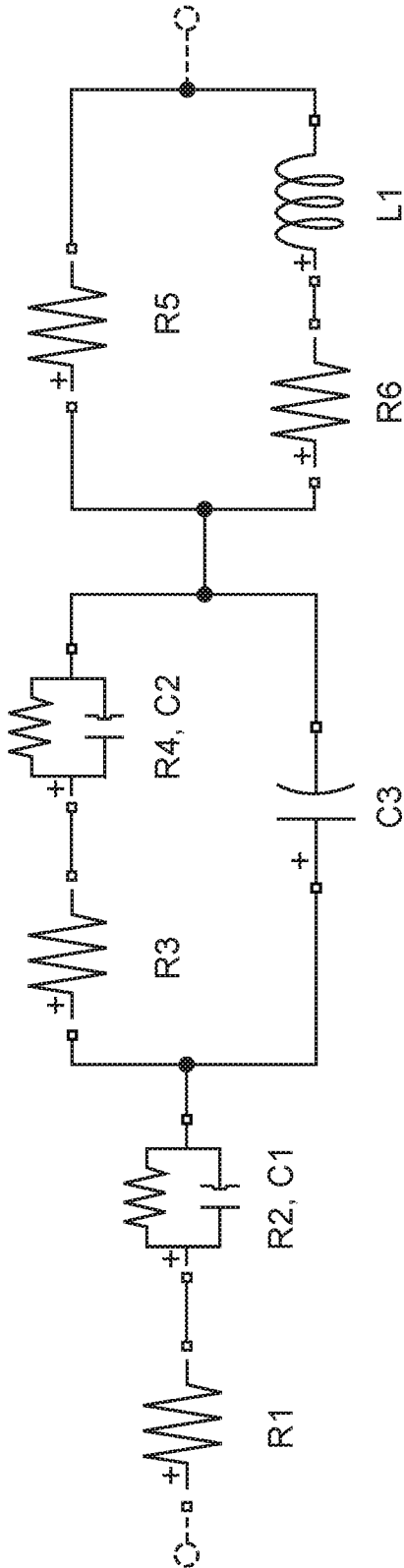


FIG. 3

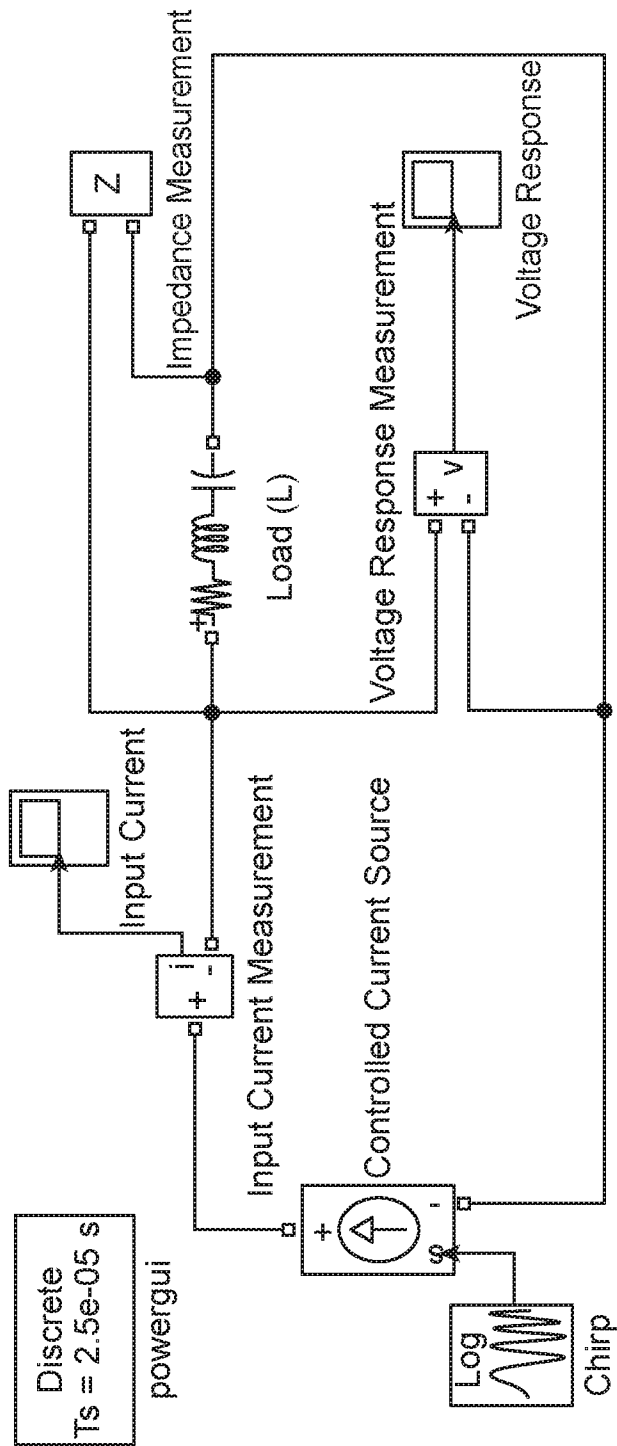


FIG. 4

4 / 15

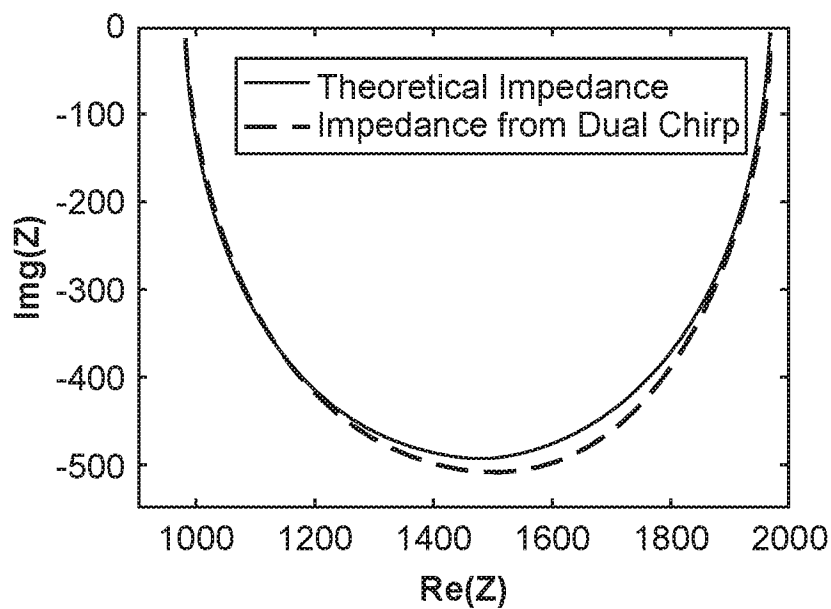


FIG. 5A

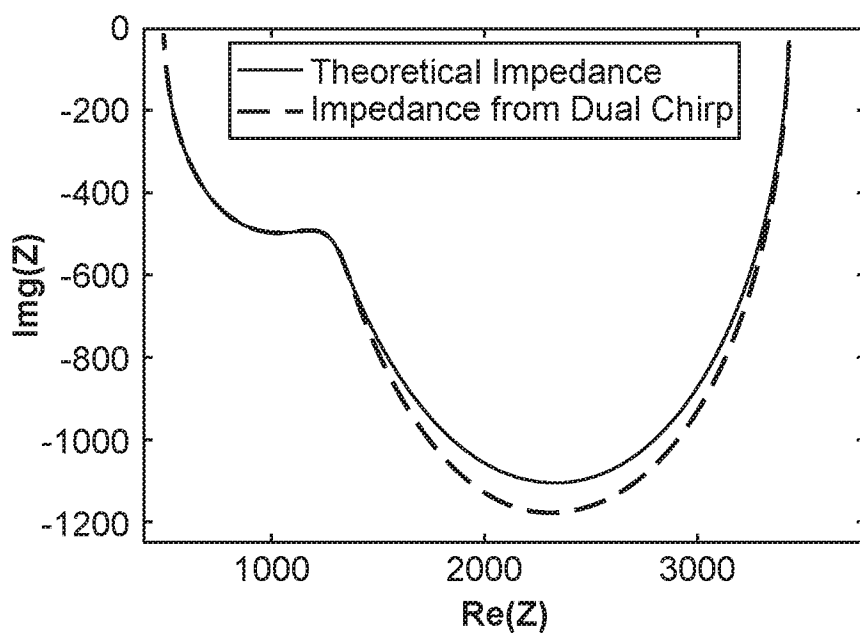


FIG. 5B

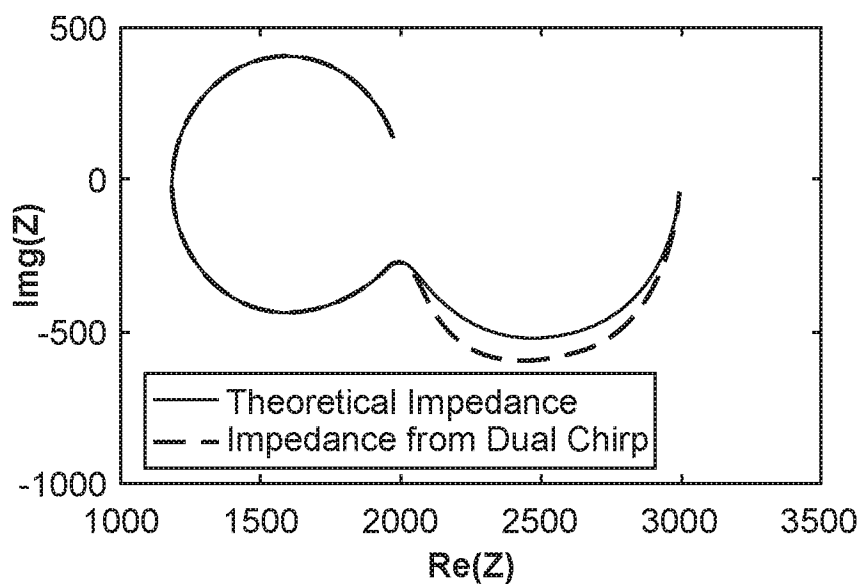


FIG. 5C

5 / 15

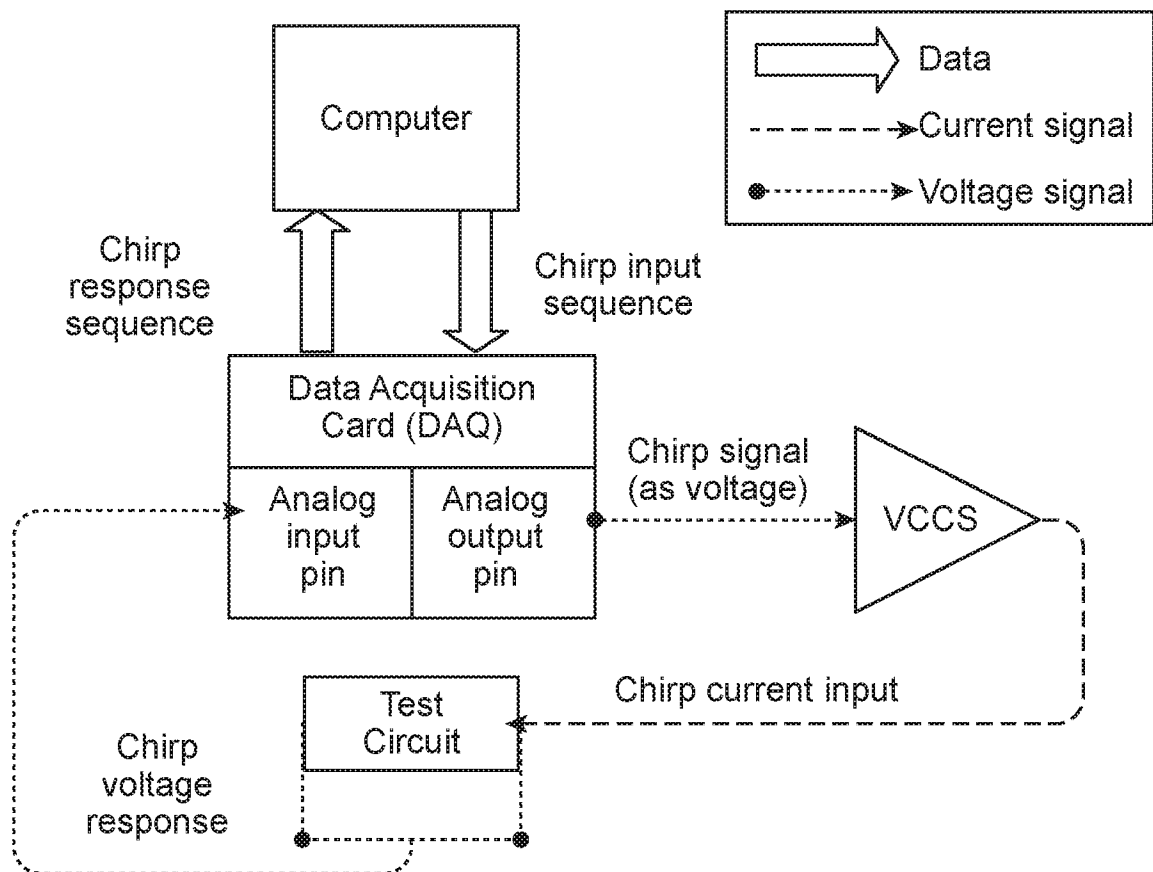


FIG. 6A

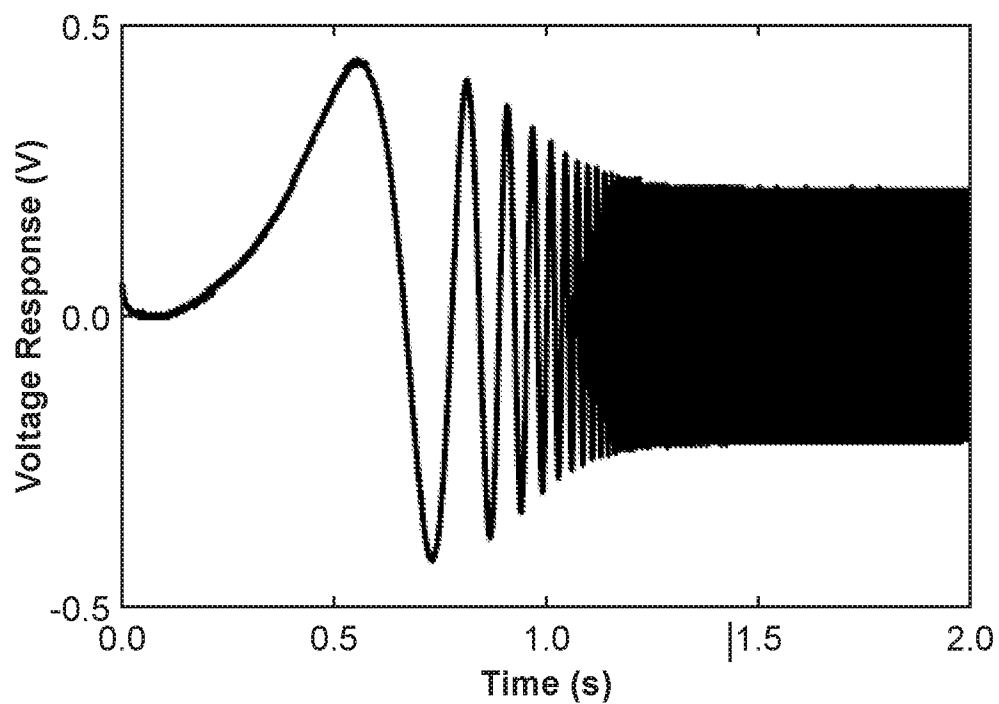


FIG. 6B

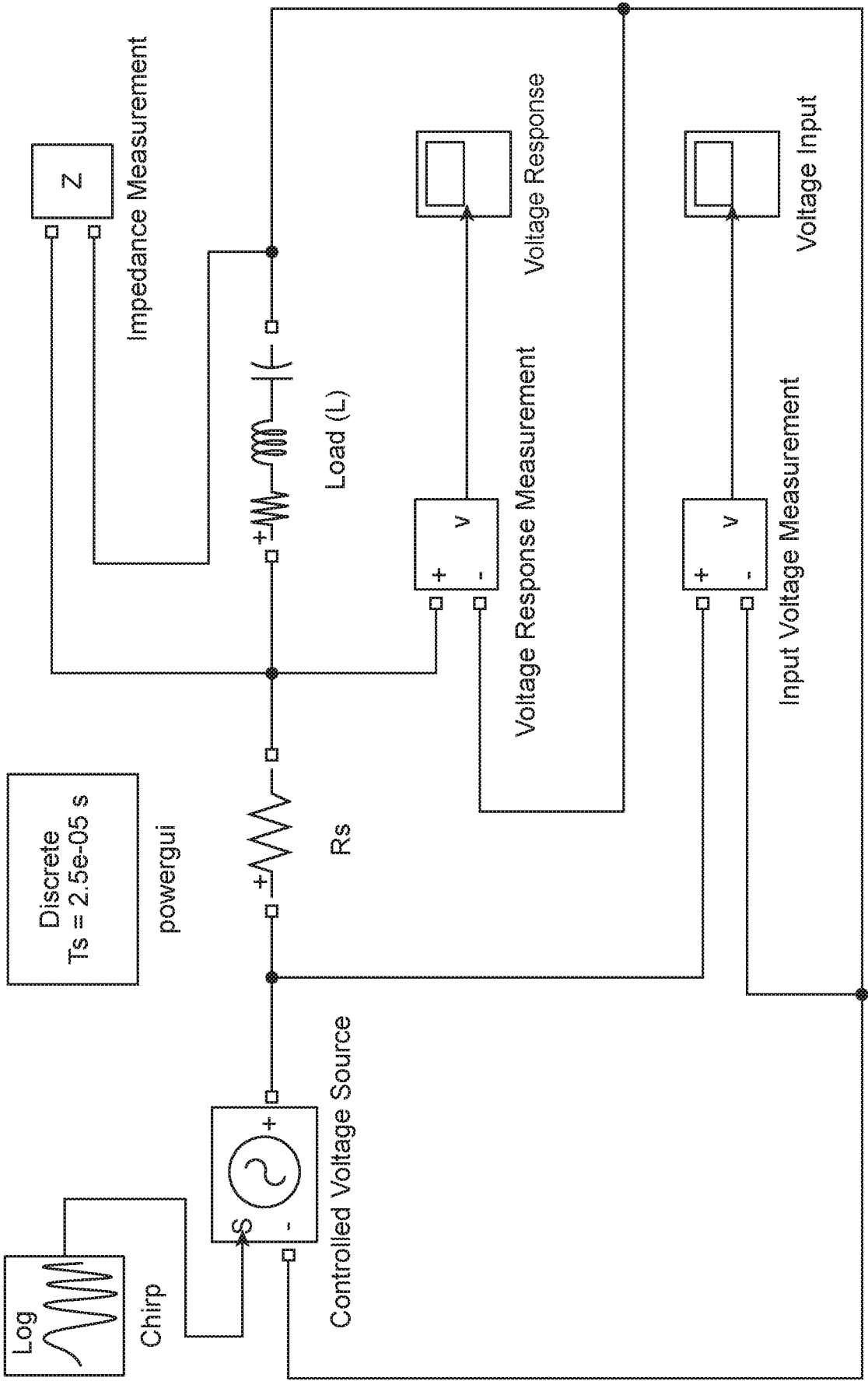


FIG. 7

7 / 15

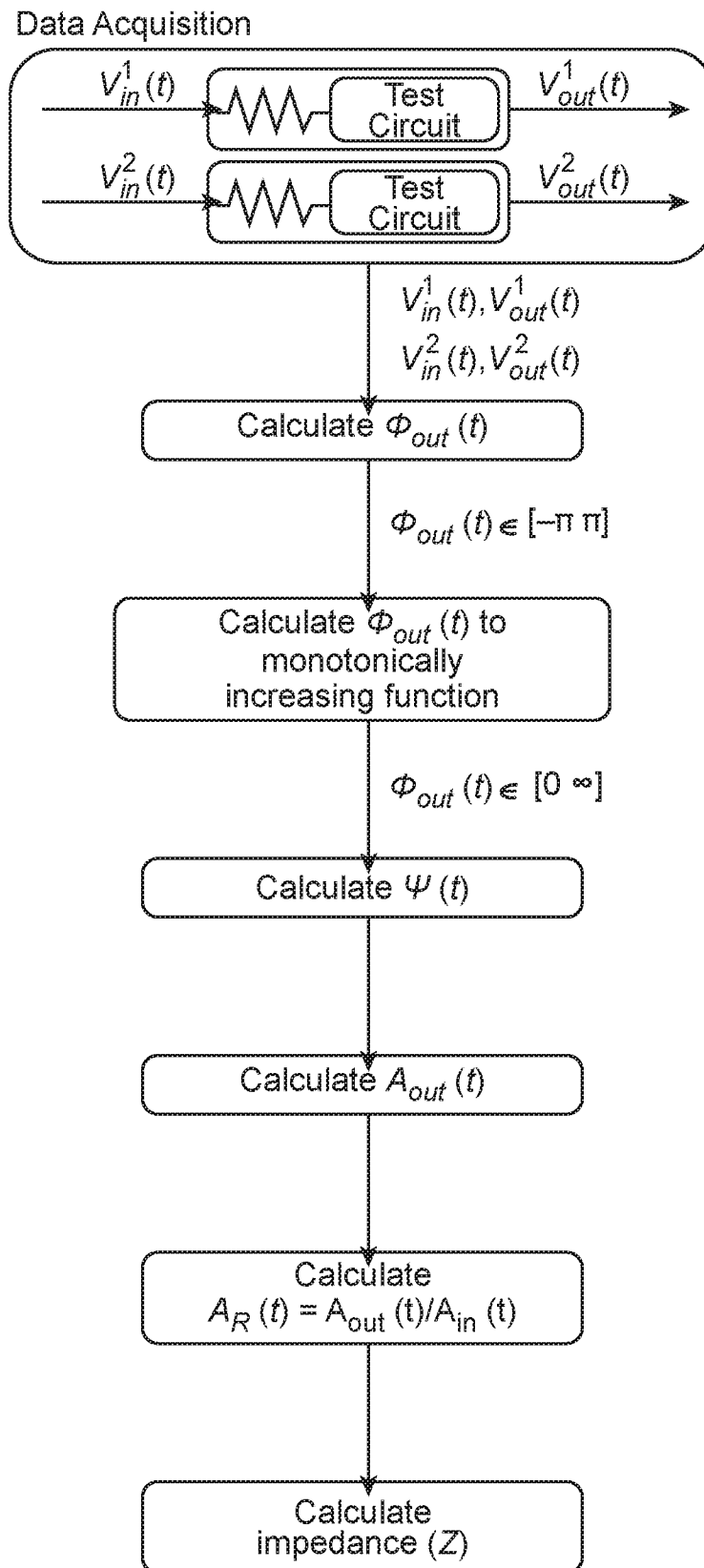


FIG. 8

8 / 15

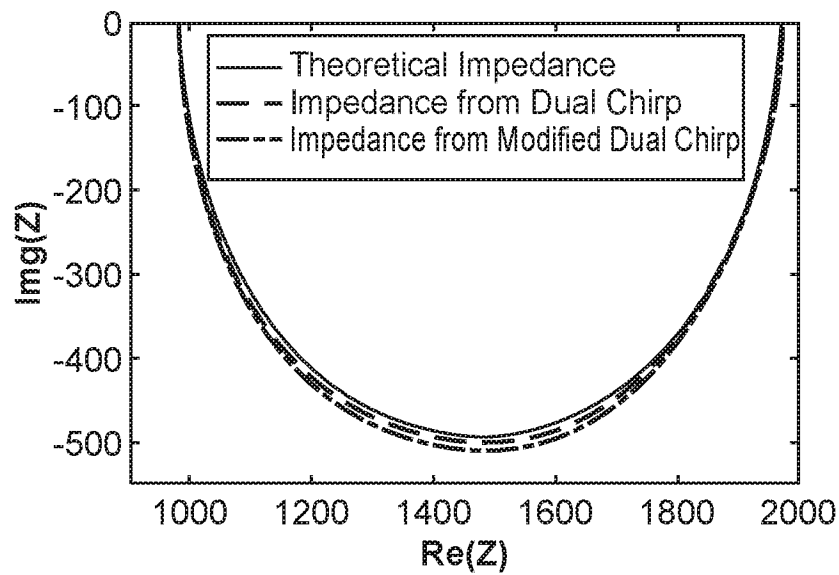


FIG. 9A

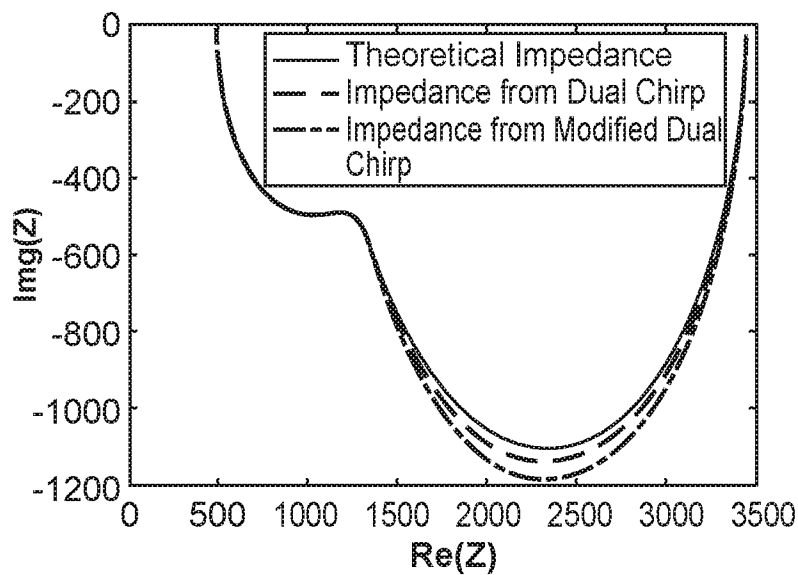


FIG. 9B

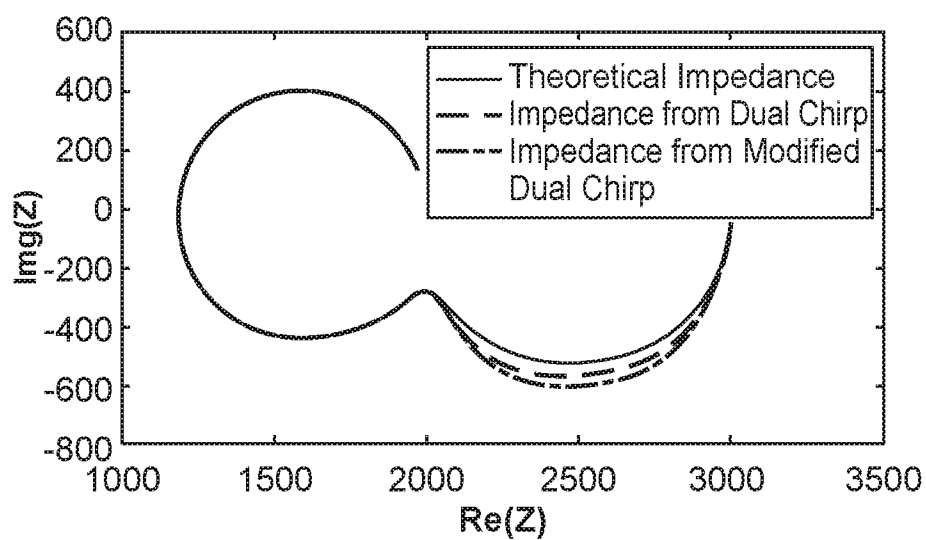


FIG. 9C

9 / 15

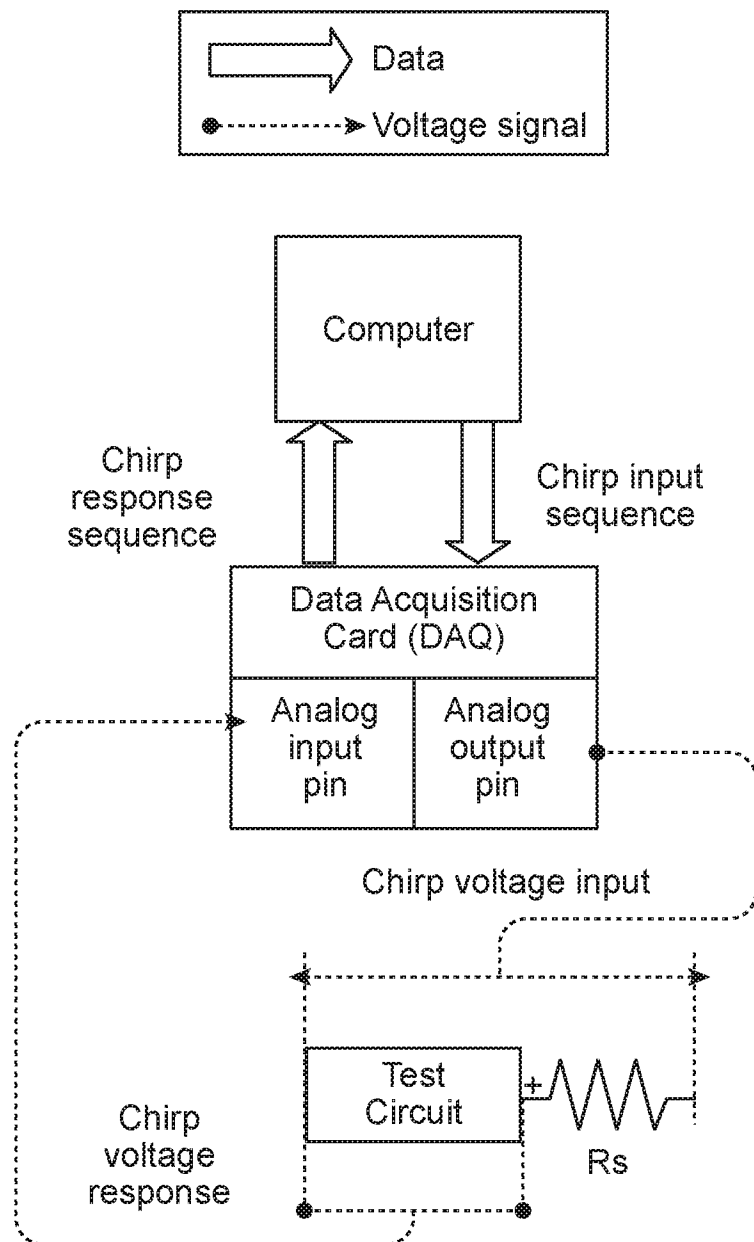


FIG. 10

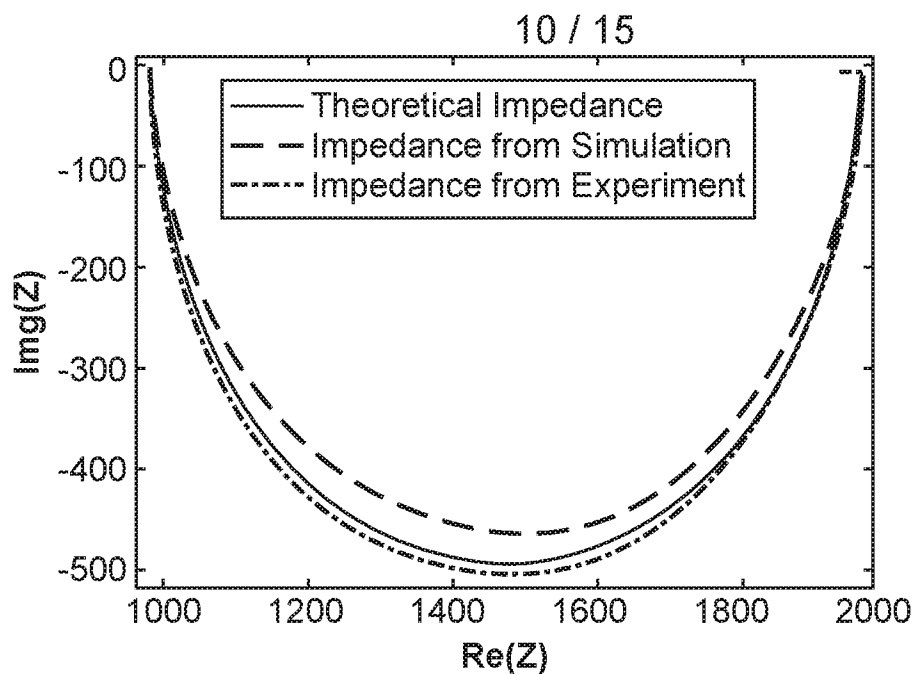


FIG. 11A

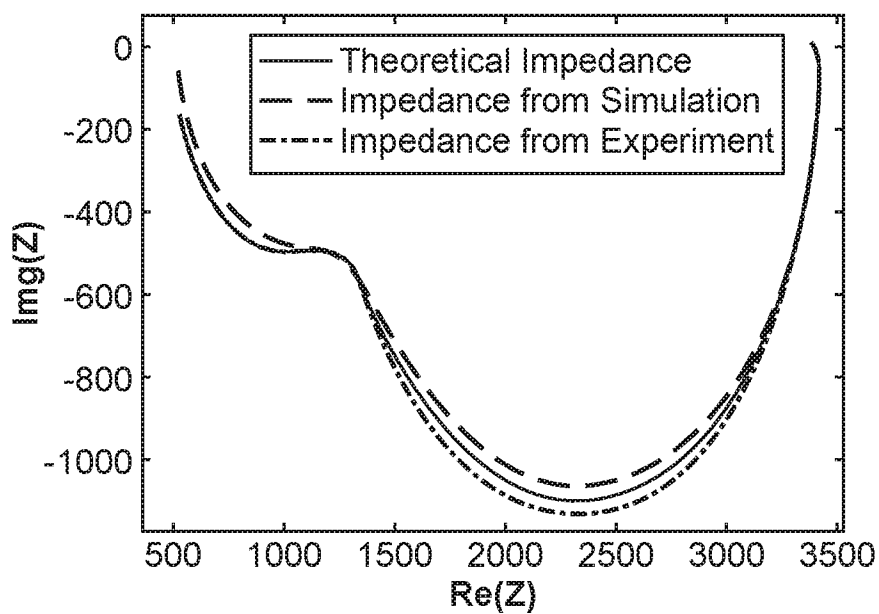


FIG. 11B

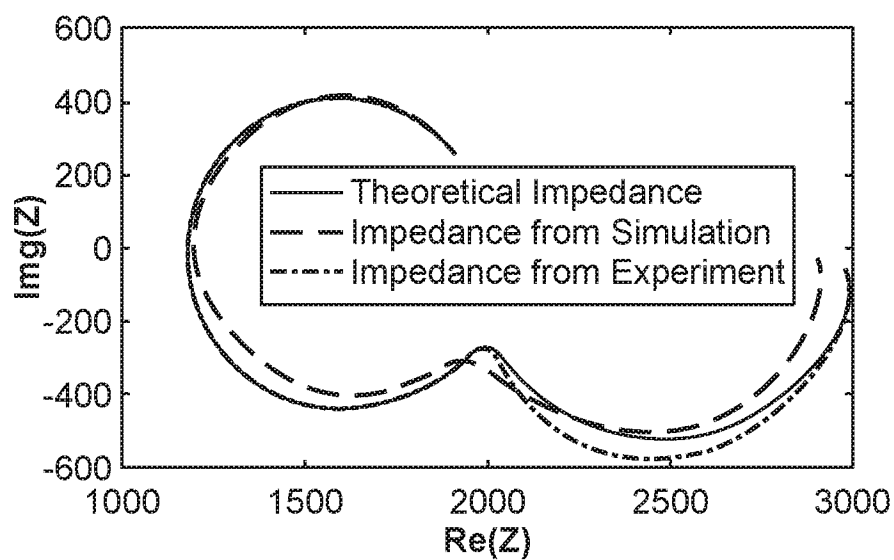


FIG. 11C

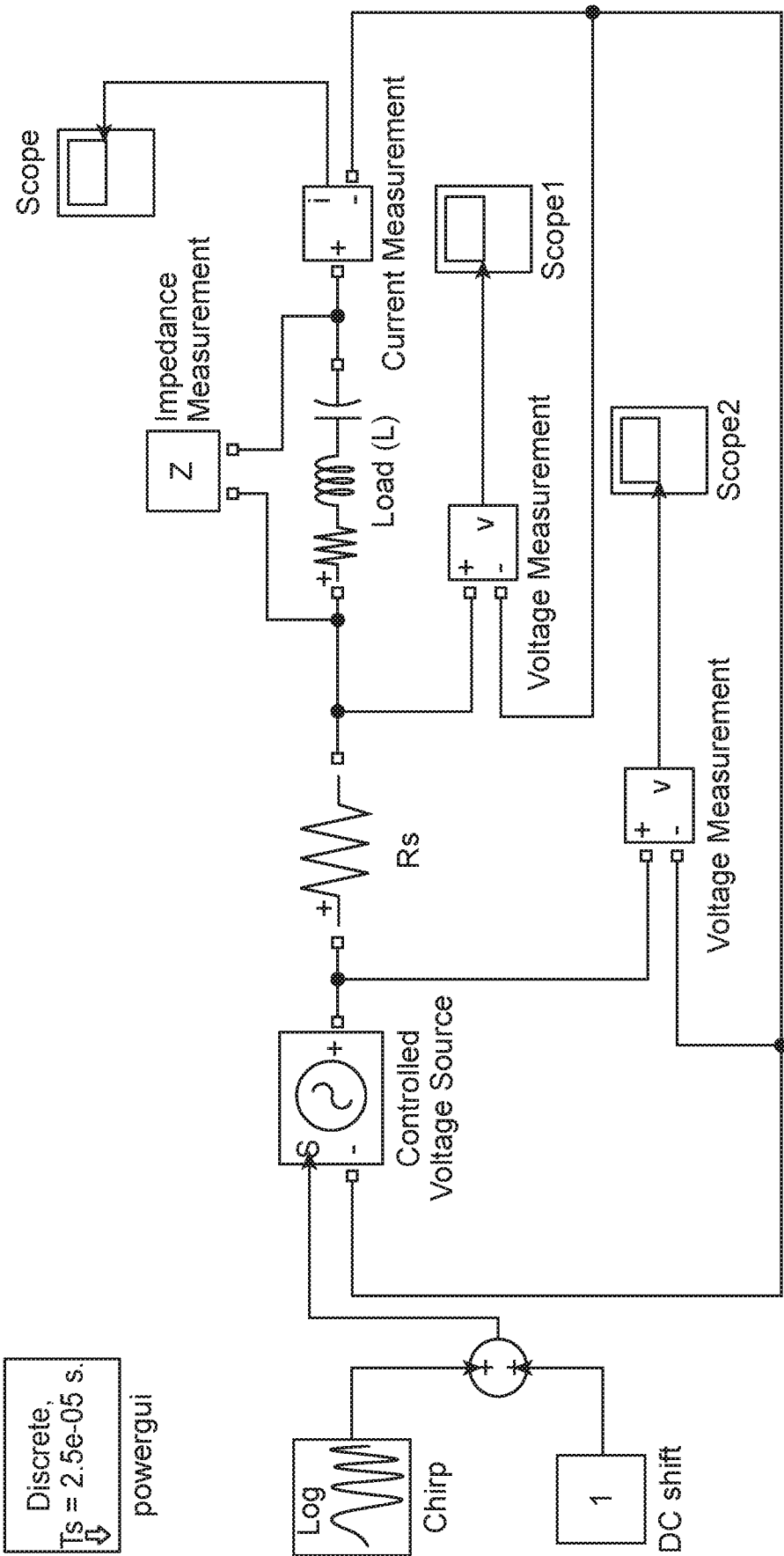


FIG. 12

12 / 15

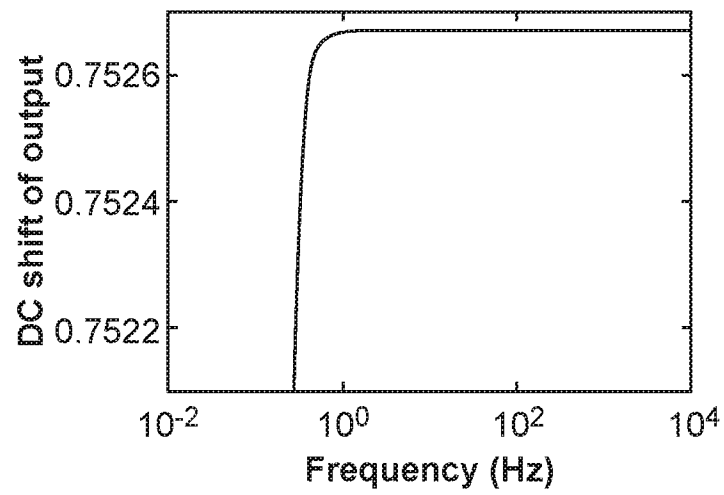


FIG. 13A

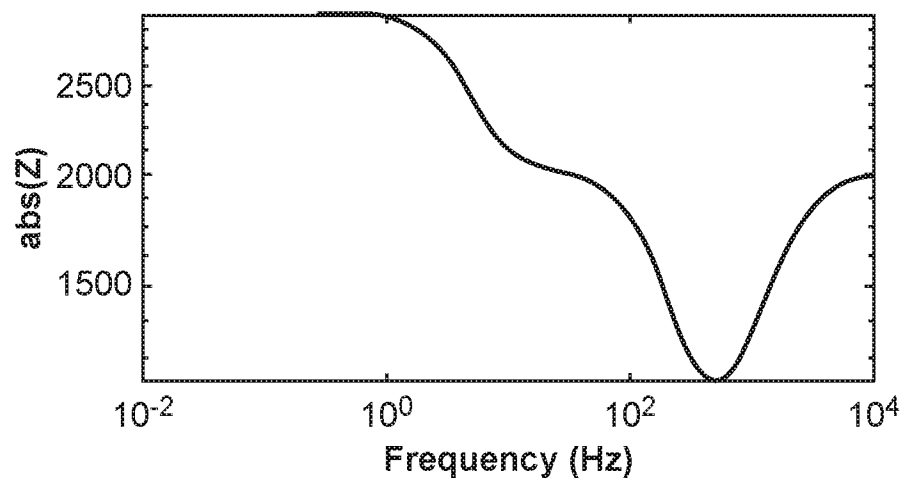


FIG. 13B

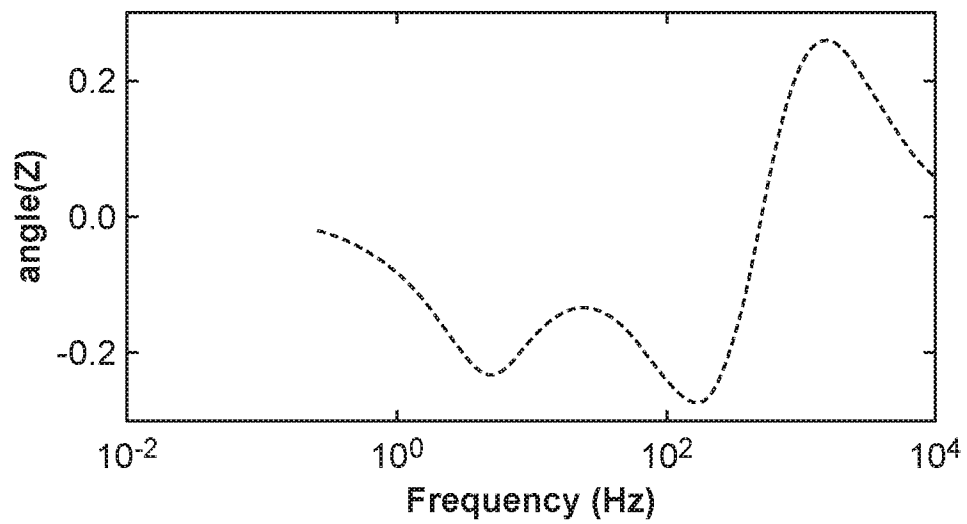


FIG. 13C

13 / 15

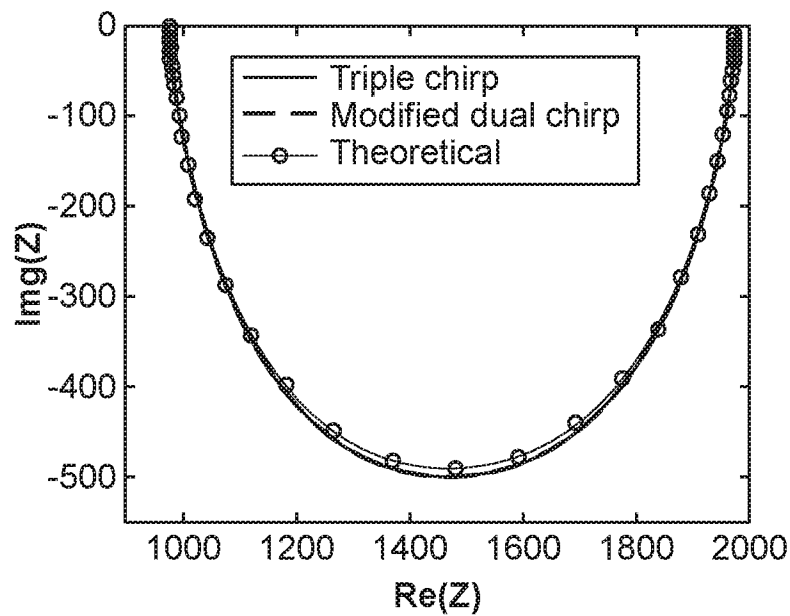


FIG. 14A

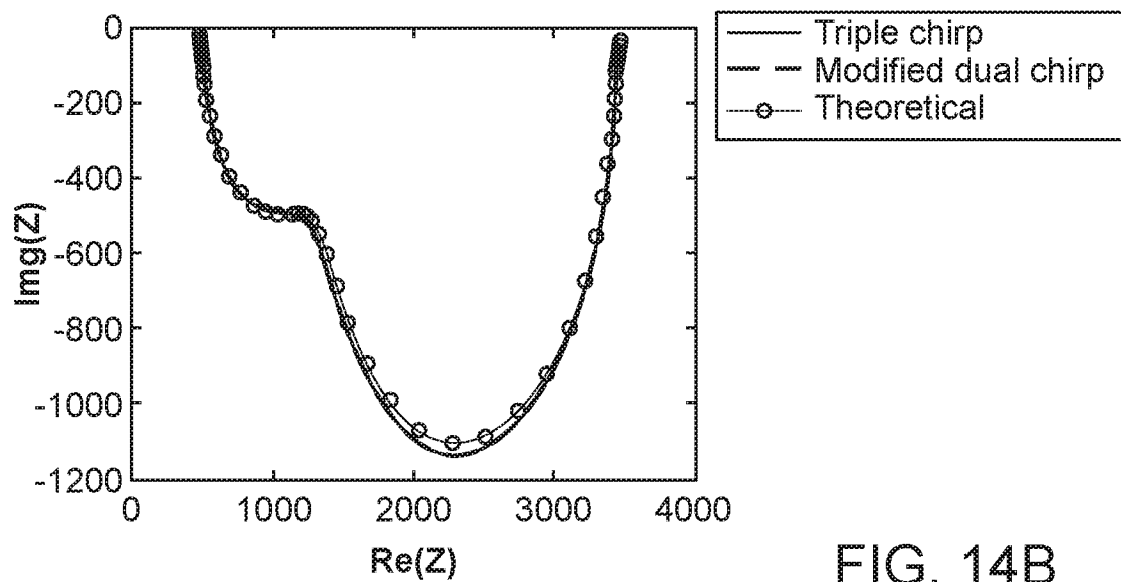


FIG. 14B

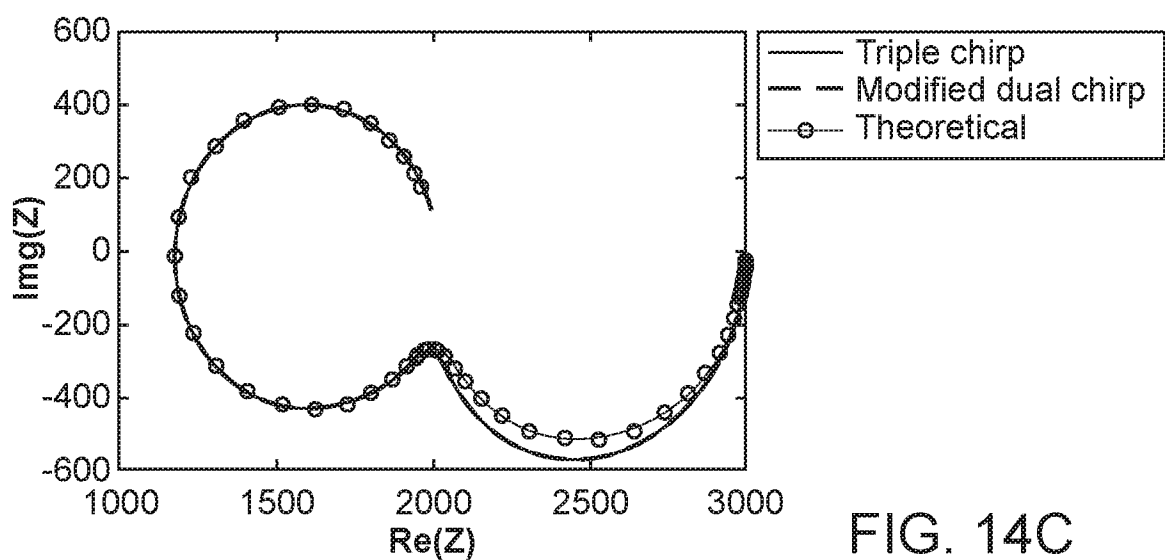


FIG. 14C

14 / 15

Data Acquisition

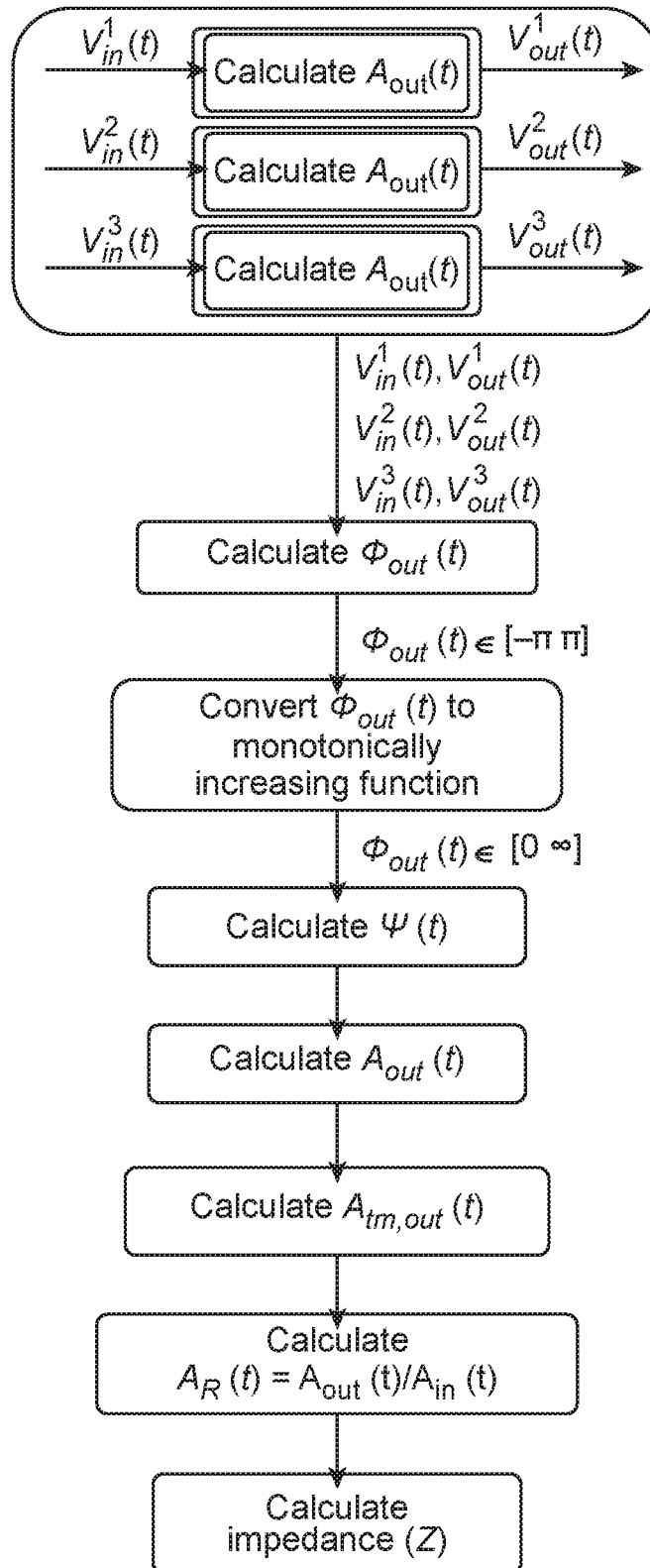


FIG. 15

15 / 15

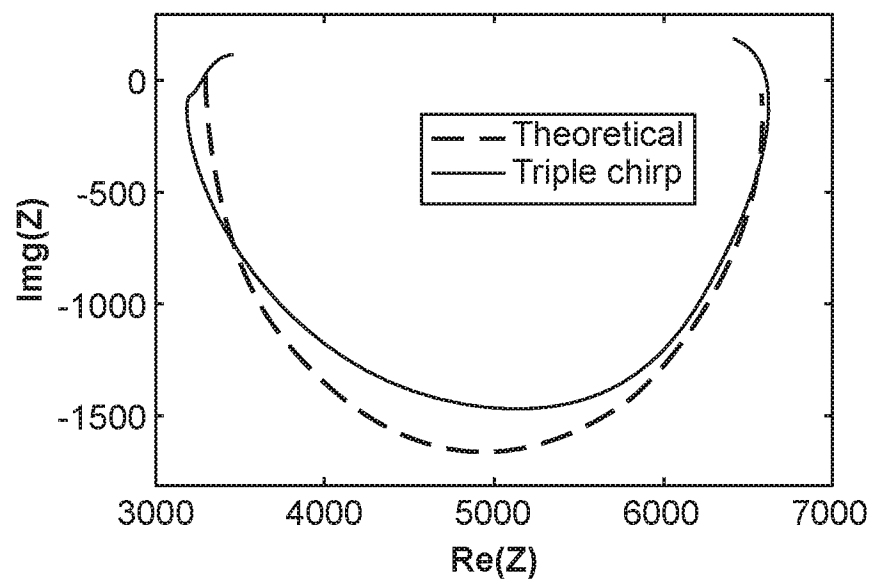


FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IN2020/050164

A. CLASSIFICATION OF SUBJECT MATTER

G01R27/02, G01R27/16, G01R25/00, G01R29/26 Version=2020.01

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

DATABASES: TotalPatent One, IPO Internal Database, WIPO PATENTSCOPE

KEYWORDS: measuring impedance, chirp signal, perturbing, response

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US20140032147A1 (VIRGINIA TECH INTELLECTUAL PROPERTIES INC HUNTINGTON INGALLS INC) 30th January 2014 (30-01-2014) [Abstract, paragraphs [0007], [0008], [0042]-[0172], [0034]-[0110], claims 1-21, figures 1-12]	1-24
Y	US20180164383A1 (FEASIBLE INC, UNIVERSITY OF CALIFORNIA) 14th June 2018 (14-06-2018) [Abstract, description, claims 1-22, figures 1-5]	1-24



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

19-06-2020

Date of mailing of the international search report

19-06-2020

Name and mailing address of the ISA/

Indian Patent Office
Plot No.32, Sector 14, Dwarka, New Delhi-110075
Facsimile No.

Authorized officer

Vipin Kumar

Telephone No. +91-1125300200

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IN2020/050164

Citation	Pub.Date	Family	Pub.Date
US 20180164383 A1	14-06-2018	WO 2018107140 A1	14-06-2018
		TW 201833578 A	16-09-2018