

BROADBAND ELECTROMAGNETIC SENSOR AND METHOD OF PRODUCING THE SAME

Technical Field

[0001] The present disclosure relates to a broadband electromagnetic sensor and method of producing the same.

Background

[0002] High-voltage power transmission and transformation equipment are an important part of power systems, and the stability of their operation is directly related to the smooth operation of the power grid. Any failure of the power grid will have a major impact on industry and society. Insulation aging or defects in high-voltage power equipment can manifest as partial discharge, which can have continuous physical effects and chemical reactions if left unchecked. Prolonged partial discharge can accelerate insulation damage and potentially harm the high-voltage power equipment. In order to ensure the safe and reliable operation of high-voltage power equipment, it is thus necessary to carry out continuous partial discharge early-stage monitoring in order to find faults as early as possible and carry out preventive replacement or repair of equipment. Partial discharge is a kind of localized electrical discharge that only partially bridges the insulation between conductors, and is usually the results of localized electrical stress concentrations in an insulator or on the surface of an insulator. Typically, partial discharge appears as pulses of much less than 1-microsecond duration. Due to the very short pulse time, the frequency range of the discharge signal can span from direct current (DC) to several gigahertz (GHz). Partial discharge is detrimental to electrical insulation with cumulative effect. It is known as one of the most conclusive indicators of the deterioration of electric insulation. Particularly, partial discharge monitoring is a significant part of insulation maintenance for covered conductors of medium voltage overhead power lines. The insulation of covered conductors prevents interphase short circuits when faults occur on it. As the value of the abnormal leakage current is very small, the standard digital relay protection is unable to react with such a low current.

[0003] Currently available methods and systems for detecting partial discharge include ultrasonic methods that however have low sensitivity and are susceptible to environmental noise. Chemical methods are not suitable for continuous monitoring and cannot detect the

severity of partial discharges. Optical technology methods are only suitable for transparent insulators. Existing current sensors are susceptible to electromagnetic interference. For example, a Rogowski coil is usually used to measure high frequency currents as well as high currents due to its air-core skeleton. The air-core skeleton makes the Rogowski coil a very popular current sensor due to many advantages such as non-magnetic-saturation, lightness, simple structure, wide dynamic bandwidth, noninvasive isolation, linearity, etc. The sensitivity and accuracy are critical indexes in evaluating the performance of Rogowski coils. However, accuracy of the Rogowski coil is susceptible to the structure of the coils and the frequency of the measured current. Furthermore, Rogowski coils are susceptible to the positions and shapes of the primary conductors.

[0004] There is a high-frequency current transformer (HFCT) sensor detection method that is widely used for partial discharge detection. In use, the HFCT sensor is clamped around the cable core, instead of the earth sheath, as this can achieve better signal-to-noise ratio. The HFCT sensor has a split core structure, consisting of an induction coil with a ferromagnetic core. The applied HFCT sensor has a bandwidth of -3 dB lower and upper cut-off frequencies at around 5 MHz and 100 MHz. This is to avoid the acquisition of on-site noise of below 1 MHz. HFCT sensors have the advantages of allowing installation during operation and the directionality of partial discharge current pulses can help in partial discharge localization purpose. However, the HFCT sensor needs to be clamped on the cable, has a large volume, has a cumbersome magnetic core, and is easily limited by high current saturation. This makes it difficult to apply in many situations where space is a constraint or where access to the cable is not available.

[0005] It is therefore desirable to provide an efficient and effective solution of partial discharge detection as a valuable tool to detect abnormal events and anomalies in medium voltage overhead lines for setting up preventive maintenance plans before the failure of electrical components occurs.

Summary

[0006] This application discloses a broadband electromagnetic sensor using a technique of electromagnetic coupling based on a theory of multimode resonators. In exemplary embodiments, the sensor is able to detect signals having frequencies ranging from around 1

MHz to 100 MHz, for example. In an exemplary embodiment of use, the sensor is configured to detect partial discharge from high-voltage power transmission and transformation equipment without requiring physical contact between the sensor and the equipment. The low-cost, light weight sensor is not affected by high current saturation, does not require use of any magnets, and is able to detect partial discharge at a distance of at least one metre away from the partial discharge source without needing to be fixed around cables of the equipment.

[0007] According to a first aspect, there is provided a method of producing a broadband electromagnetic sensor, the broadband electromagnetic sensor comprising an amplifier circuit in connection with a sensing portion, the sensing portion comprising a coil array structure of a plurality of coils wherein each coil is able to detect signals having frequencies within its own frequency bandwidth and wherein the coil array structure is able to detect signals having frequencies within a frequency bandwidth of the broadband electromagnetic sensor, the method comprising the steps of:

- (a) representing the sensing portion as a theoretical circuit wherein each coil of the plurality of coils is represented by a theoretical inductor having a theoretical inductance, and performing circuit simulation of the theoretical circuit to obtain circuit simulation results of the theoretical circuit and to obtain the theoretical inductance of each coil;
- (b) calculating a length of each coil from its theoretical inductance using a predetermined method, and plotting an integrated layout of the plurality of coils according to the calculated length of each coil;
- (c) creating a coil model of each coil in the integrated layout using an electromagnetic simulation software, and performing electromagnetic simulation of the coil model to obtain electromagnetic simulation results of the coil model;
- (d) creating a coil equivalent circuit model of each coil model wherein each coil model is represented as an inductor provided in parallel connection with a capacitor and in series connection with a resistor, and performing circuit simulation of the coil equivalent circuit model to obtain circuit simulation results of the coil equivalent circuit model and to determine for each coil model its inductance, resistance and capacitance when the circuit simulation results of the coil equivalent circuit model best fit the electromagnetic simulation results of the coil model;

- (e) creating a two-coil model of two coils in the integrated layout using two coil models that had been created in step (c), and performing electromagnetic simulation of the two-coil model to obtain electromagnetic simulation results of the two-coil model;
- (f) creating a two-coil equivalent circuit model of the two-coil model using two coil equivalent circuit models that had been created in step (d), wherein the two-coil equivalent circuit model includes a mutual inductance in the two-coil model, and performing circuit simulation of the two-coil equivalent circuit model to obtain circuit simulation results of the two-coil equivalent circuit model and to determine the mutual inductance in the two-coil model when the circuit simulation results of the two-coil equivalent circuit model best fit the electromagnetic simulation results of the two-coil model;
- (g) repeating steps (e) and (f) for every distinct pair of coils in the integrated layout to determine the mutual inductance between every distinct pair of coils in the integrated layout;
- (h) creating an integrated layout equivalent circuit model using all the coil equivalent circuit models that had been created in step (d), wherein the integrated layout equivalent circuit model includes the mutual inductances between every distinct pair of coils in the integrated layout, and performing circuit simulation of the integrated layout equivalent circuit model to obtain circuit simulation results of the integrated layout equivalent circuit model and to determine for each coil model its optimized inductance when the circuit simulation results of the integrated layout equivalent circuit model best fit the circuit simulation results of the theoretical circuit;
- (i) recalculating the length of each coil from its optimized inductance using the predetermined method and replotting the integrated layout of the plurality of coils according to the recalculated length of each coil; and
- (j) fabricating the coil array structure on a printed circuit board according to the replotted integrated layout.

[0008] The theoretical circuit in step (a) may comprise a ladder structure similar to a bandpass filter wherein each element of the ladder structure comprises one of the theoretical inductors in electrical connection with a theoretical capacitor, and wherein each element is configured according to a preselected response type.

[0009] The preselected response type may be one of: a Butterworth response, a Chebyshev response, and an elliptic response.

[0010] The method may further comprise, after step (h), creating a circuit validation model of the two coils that includes the confirmed mutual inductance between the two coils and performing circuit simulation of the circuit validation model to obtain circuit simulation results of the circuit validation model, wherein fitting of the circuit simulation results of the circuit validation model with the circuit simulation results of the two-coil equivalent circuit model confirms the mutual inductance between the two coils.

[0011] The circuit validation model of the integrated layout may comprise a T-type circuit.

[0012] The electromagnetic simulation results and the circuit simulation results may include variation of input impedance and scattering parameter with frequency.

[0013] The method may further comprise fabricating the amplifier circuit on the printed circuit board and connecting the amplifier circuit with the coil array structure.

[0014] The method may further comprise, after step (i), creating an integrated replotted layout model of the replotted integrated layout using the electromagnetic simulation software, performing electromagnetic simulation of the integrated replotted layout physical model to obtain electromagnetic simulation results of the integrated replotted layout physical model, and comparing the electromagnetic simulation results of the integrated replotted layout physical model with the circuit simulation results of the theoretical circuit to confirm the recalculated lengths of each coil.

[0015] According to a second aspect, there is provided a broadband electromagnetic sensor comprising: an amplifier circuit having at least 26 dB gain through its bandwidth; and a sensing portion comprising a coil array structure of a plurality of coils, wherein each coil has a different length from other coils in the plurality of coils and detects signals having frequencies within its own frequency bandwidth, such that the plurality of coils are together able to detect signals having frequencies within a frequency bandwidth of the sensor, and wherein the frequency bandwidth of the sensor ranges from around 1 MHz to 100 MHz, such that the sensor is able to detect partial discharge from high voltage equipment without being in physical contact with the high voltage equipment.

[0016] The coil array structure may be provided as an integrated layout on a printed circuit board, wherein the integrated layout is optimized to minimize area of the printed circuit board required to support the coils.

[0017] Each coil may be represented by an equivalent circuit model comprising a capacitor provided in parallel connection with an inductor and the inductor provided in series connection with a resistor.

[0018] The sensing portion may be represented by an equivalent circuit model that incorporates mutual inductance between every distinct pair of coils in the coil array.

[0019] The coil array structure comprises one of: a rectangular shape, a circular shape, a three-dimensional structure.

[0020] The broadband electromagnetic sensor may be produced by the method of the first aspect.

Brief Description of the Drawings

[0021] In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments of the present invention, the description being with reference to the accompanying illustrative drawings.

FIG. 1 is a schematic illustration of a single coil and its corresponding impedance parameter plot when it detects an electromagnetic wave signal.

FIG. 2 is graphs of input and output magnitudes in the frequency and time domains when an input electromagnetic wave signal is detected by the single coil of FIG. 1.

FIG. 3 is a schematic illustration of a two-coil system and its corresponding impedance parameter plot when it detects an electromagnetic wave signal.

FIG. 4 is graphs of input and output magnitudes in the frequency and time domains when an input electromagnetic wave signal is detected by the two-coil system of FIG. 3.

FIG. 5 is an exemplary integrated layout equivalent circuit model of an exemplary broadband electromagnetic sensor.

- FIG. 6 is an exemplary bandpass filter ladder structure circuit representing a radiator or broadband sensing portion of the broadband electromagnetic sensor.
- FIG. 7 is a schematic illustration of a printed circuit board assembly of an exemplary broadband electromagnetic sensor comprising a sensing portion in connection with an amplifier circuit.
- FIG. 8 is a photograph of a printed circuit board assembly fabricated according to the schematic of FIG. 7.
- FIG. 9 is a schematic illustration of an integrated layout of an exemplary four-coil system for the sensing portion of the broadband electromagnetic sensor of FIGS. 7 and 8.
- FIG. 10 is a graph of input impedance of the integrated layout equivalent circuit model of FIG. 5.
- FIG. 11 is an exemplary embodiment of an amplifier circuit of the broadband electromagnetic sensor.
- FIG. 12(a) is an exemplary coil model of an exemplary first coil of the four-coil system of FIG. 9.
- FIG. 12(b) is a first exemplary coil equivalent circuit model of the coil model of FIG. 12(a).
- FIG. 12(c) is a graph of input impedance of the coil model of FIG. 12(a).
- FIG. 12(d) is a second exemplary coil equivalent circuit model of the coil model of FIG. 12(a).
- FIG. 12(e) is a graph of input impedance of the coil equivalent circuit model of FIG. 12(c).
- FIG. 13(a) is an exemplary coil model of an exemplary second coil of the four-coil system of FIG. 9.
- FIG. 13(b) is a graph of input impedance of the coil model of FIG. 13(a).
- FIG. 13(c) is an exemplary coil equivalent circuit model of the coil model of FIG. 13(a).
- FIG. 13(d) is a graph of input impedance of the coil equivalent circuit model of FIG. 13(c).
- FIG. 14(a) is an exemplary two-coil model of an exemplary two-coil system comprising the coil model of FIG. 13(a) and the coil model of FIG. 14(a).
- FIG. 14(b) is a graph of input impedance of the two-coil model of FIG. 14(a).
- FIG. 14(c) is an exemplary two-coil equivalent circuit model of the two-coil model of FIG. 14(a).
- FIG. 14(d) is a graph of input impedance of the two-coil equivalent circuit model of FIG. 14(c).

FIG. 14(e) is an exemplary T-type circuit validation model of the exemplary two-coil system of FIG. 14(a).

FIG. 14(f) is a MATLAB calculation of input impedance of the T-type circuit validation model of FIG. 14(e).

FIG. 15 is a photograph of a fabricated broadband electromagnetic sensor comprising the printed circuit board assembly of FIG. 8.

FIG. 16 is a schematic illustration of assembly steps of a broadband electromagnetic sensor.

FIG. 17 is a schematic illustration of a set-up to test the fabricated broadband electromagnetic sensor of FIG. 16.

FIG. 18 is a graph of exemplary measured waveforms obtained using an HFCT sensor and using the fabricated broadband electromagnetic sensor of FIG. 16 when detecting partial discharge.

FIG. 19 is a photograph of actual high voltage equipment having units of the sensor of FIG. 16 attached to multiple cable of the equipment.

FIG. 20 is a graph of a phase-resolved partial discharge pattern obtained from the set-up of FIG. 19.

FIG. 21 is a flowchart of an exemplary method of producing a broadband electromagnetic sensor.

Detailed Description

[0022] Exemplary embodiments of a method 90 of producing a broadband electromagnetic sensor 10 and exemplary embodiments of the broadband electromagnetic sensor 10 will be described with reference to FIGS. 1 to 21 in which the same reference numerals are used across the figures to refer to the same or similar parts.

[0023] Normally, a single coil as shown in FIG. 1 has a narrow frequency bandwidth with a high quality factor. When plane electromagnetic (EM) waves radiate at a single coil as shown in FIG. 1, from the frequency domain, if the input spectrum is broadband, the output spectrum is a narrow band, and from the time domain, if the input signal is a chirp signal, the output signal is a sinusoidal signal with attenuated amplitude, as can be seen in FIG. 2. The simulated results verifies that the single coil resonates at a narrow frequency bandwidth, as can be seen in FIG. 1. When plane EM waves radiate at a two-coil system as shown in FIG. 3, from the

frequency domain, if the input spectrum is kept being broadband, the output spectrum has two narrow bands, and from the time domain, if the input signal is also a chirp signal, the output signal has more frequency components, as shown in FIG. 4. The simulated results verifies that the two-coil system resonates at two narrow bands, as shown in FIG.3.

[0024] By increasing the number of cascaded or parallel coils in a system, the system can generate multiple resonant frequencies so that it can receive/radiate time domain signals of multiple frequencies. Due to frequency response non-flatness, the system can effectively receive/radiate signals with discontinuous frequencies. The presently disclosed broadband electromagnetic sensor 10 is thus made of several coils, along with several added capacitors, as shown in an exemplary integrated layout equivalent circuit model of FIG. 5. In an exemplary embodiment, the broadband electromagnetic sensor 10 comprises an amplifier circuit 20 (FIG. 6) in electrical connection with a sensing portion 30 as shown in the printed circuit board assembly in FIGS. 7 and 8. The amplifier circuit 20 may comprise an associated improvement circuit added to amplify the input analog signal, having at least 26 dB gain through its bandwidth. The sensing portion 30 comprises a coil array structure 37 of a plurality of planar or three-dimensional coils or inductors (31, 31, 33, 34, FIG. 9) accompanied by one or more capacitors to tune their resonant frequencies. Each coil 31, 32, 33, 34 is able to detect signals having frequencies within its own frequency bandwidth and the coil array structure 37 is able to detect signals having frequencies within a frequency bandwidth of the broadband electromagnetic sensor 10. The required centre frequency of each coil 31, 31, 33, 34 and its bandwidth relates to the order of bandpass filter. Scattering parameters of the sensing portion 30 are shown in FIG. 10, indicating that the broadband sensing feature is obtained.

[0025] In an exemplary method 90 (FIG. 21) of producing the broadband electromagnetic sensor 10, the sensing portion 30 may be represented as a theoretical circuit 39 as shown in FIG. 11. In the theoretical circuit 39, each coil of the plurality of coils 31, 32, 33, 34 may be represented by a theoretical inductor having a self-inductance (or theoretical inductance) L' . The theoretical circuit 39 may comprise a ladder structure similar to a bandpass filter wherein each element (indicated by dotted lines) of the ladder structure comprises one of the theoretical inductors in electrical connection with a theoretical capacitor having a theoretical capacitance C' . Each element is configured according to a preselected response type. The response type may be a Butterworth response, a Chebyshev response, or an elliptic response, for example. The theoretical inductor and theoretical capacitor of each element may be in a series or a parallel

relationship with each other depending on the preselected response type, and the elements in the ladder structure may have different response types from each other.

[0026] Based on the selected frequency response type, the centre frequency, and the bandwidth of the sensor 10, the order and theoretical element values L' and C' of each element in the ladder structure theoretical circuit 39 may be confirmed by performing circuit simulation of the theoretical circuit 39 to obtain circuit simulation results of the theoretical circuit 39 and to obtain the theoretical inductance L' of each coil (901, FIG. 21). The circuit simulation results may comprise an input impedance of the theoretical circuit 39.

[0027] From the obtained theoretical inductance L' of each coil 31, 32, 33, 34, a known method such as that described in the publication “H. Greenhouse, ‘Design of Planar Rectangular Microelectronic Inductors,” in IEEE Transactions on Parts, Hybrids, and Packaging, vol. 10, no. 2, pp. 101-109, June 1974’ may be applied to estimate the length of each coil 31, 32, 33, 34 according to the self-inductances. In other words, the length of each coil 31, 32, 33, 34 may be calculated using a predetermined method. Other exemplary methods for calculating coil length from the theoretical inductance L' of the coil 31, 32, 33, 34 may be found in the following publications “S. D. Barman, A. W. Reza, N. Kumar, Md. E. Karim, A. B. Munir, ‘Wireless powering by magnetic resonant coupling: Recent trends in wireless power transfer system and its applications,’ Renewable and Sustainable Energy Reviews, 2015’ and “T. Imura and Y. Hori, ‘Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula,’ IEEE Transactions on Industrial Electronics, vol. 58, no. 10, Oct. 2011”. Having calculated the length of each coil, an integrated layout 38 (FIG. 9) of the plurality of coils 31, 32, 33, 34 is plotted according to the calculated length of each coil (902, FIG. 21). Preferably, the integrated layout 38 minimizes area of a printed circuit board 50 on which the actual coils of the coil array structure 27 will be fabricated.

[0028] In general, before connecting the coils 31, 32, 33, 34 together by vias and traces after printing of the coils 31, 32, 33, 34 on the printed circuit board, the coils 31, 32, 33, 34 which are represented by the theoretical inductors 100, 200, 300, 400 are simulated (electromagnetic simulation and circuit simulation) to extract the actual self-inductances of the coils and mutual inductances between them. The coils 31, 32, 33, 34 are then connected together as a ladder structure similar to a bandpass filter, along with the added capacitors, and again simulated (electromagnetic simulation) to obtain electromagnetic simulation results that may comprise

change of the input impedance and scattering parameter with frequency. Meanwhile, an equivalent circuit model 45 of the sensing portion 30 of the broadband electromagnetic sensor 10 is constructed to obtain circuit simulation results (FIG. 10) that may comprise change of the input impedance and scattering parameter, by using the self and mutual inductances extracted. According to the basic definition of the resistance of conductors and capacitance between conductors, the resistances and the self-capacitances of the coils 31, 32, 33, 34 are calculated and taken into consideration in the equivalent circuit model 45 of the sensing portion 30. The input impedance diagram of the equivalent circuit model 45 may have some difference compared to the theoretical input impedance of the theoretical circuit 39, due to the mutual inductance effect and modelling issues. After optimization of the equivalent circuit model 45 for the theoretical values, the lengths of the coils 31, 32, 33, 34 are recalculated and the design procedure is repeated to obtain a more precise electromagnetic sensor 10. The above steps are described in greater detail below.

[0029] In the exemplary method 90, a coil model 40 (FIG. 12(a), FIG. 13(a)) of each coil 31, 32, 33, 34 in the integrated layout 38 is created using an electromagnetic simulation software, followed by performing electromagnetic simulation of the coil model 40 to obtain electromagnetic simulation results (FIG. 12(c)) of the coil model 40 (903, FIG. 21). A coil equivalent circuit model 41 (FIGS. 12(b), 12(d)) of each coil model 40 is also created wherein each coil model 40 is represented as an inductor provided in parallel connection with a capacitor and in series connection with a resistor. Circuit simulation of the coil equivalent circuit model 41 is then performed to obtain circuit simulation results (FIG. 12(e), FIG. 13(d)) of the coil equivalent circuit model 41. For each coil model 40, given the resonance, its inductance, resistance and capacitance is tuned until the circuit simulation results (FIG. 12(e), FIG. 13(d)) of the coil equivalent circuit model 41 best fits with the electromagnetic simulation results (FIG. 12(c), FIG. 13(b)) of the coil model 40 (904, FIG. 21), thereby determining the inductance, resistance and capacitance at resonance of each coil model 40 for each coil 31, 32, 33, 34.

[0030] Appreciably, there arises mutual inductance whenever two coils are provided in close proximity. To determine the mutual inductance between every distinct pair of coil models among all the coil models 40 that had been created earlier, a two-coil model 42 of two coils in the integrated layout 38 is first created using two coil models 40 that had been created earlier. In an exemplary embodiment of a two-coil model 42 comprising two coil models 40 Coil 1 and Coil as shown in FIG. 14(a), specifications of the two-coil model 42 may be as follows. All

trace widths are 1mm. All gaps between traces are 0.4 mm. Copper trace thickness is 0.018 mm. printed circuit board base material FR4 substrate dielectric constant ϵ_r is 4.2 and thickness is 0.2 mm. Coil 1 has three turns, and Coil 2 has two turns. Add external capacitors in parallel for each coil and then make them resonate at 10 MHz. Frequency range is from 0.1 MHz to 10 MHz. Electromagnetic simulation of the two-coil model 42 is performed to obtain electromagnetic simulation results of the two-coil model 42 as shown in FIG. 14(b) (905, FIG. 21).

[0031] Then, a two-coil equivalent circuit model 43 of the two-coil model 42 is created using two relevant coil equivalent circuit models 41 that had earlier been created. Notably, the two-coil equivalent circuit model 43 includes a mutual inductance M_{ab} in the two-coil model 42 as can be seen in FIG. 14(c), which may be achieved by adding coupling by the circuit simulation tool. By performing circuit simulation of the two-coil equivalent circuit model 43 to obtain circuit simulation results of the two-coil equivalent circuit model 43 as shown in FIG. 14(d), the mutual inductance M_{ab} can be tuned to best fit the circuit simulation results (FIG. 14(d)) of the two-coil equivalent circuit model 43 with the electromagnetic simulation results (FIG. 14(b)) of the two-coil model 42, thereby determining the mutual inductance M_{ab} in the two-coil model 42 (906, FIG. 21). These steps 905, 906 are repeated for every distinct pair of coils in the integrated layout 98 to determine the mutual inductance between every distinct pair of coils in the integrated layout 38 (907, FIG. 21). Thus, when the circuit simulation results (FIG. 14(d)) of the two-coil equivalent circuit model 43 with coupling or mutual inductance is consistent with the electromagnetic simulation results (FIG. 14(b)), the mutual inductance M_{ab} between two coils is confirmed and solved.

[0032] Optionally, a circuit validation model 44 of the two coil models 40 may be created that includes the confirmed mutual inductance M_{ab} in the two-coil model 42 may be created as shown in FIG. 14(e). Circuit simulation of the circuit validation model 44 may then be performed, for example using MATLAB, to obtain circuit simulation results of the circuit validation model 44 that may comprise Z_e , the input impedance of the circuit validation model 44. The circuit validation model 44 may be optimized using MATLAB by tuning the mutual inductance M_{ab} , capacitances and resistances in the circuit validation model 44 so that the circuit simulation results (FIG. 14(f)) best fit the circuit simulation results (FIG. 14(d)) of the two-coil

equivalent circuit model 43. The two-coil equivalent circuit model 43 can then be completed with the confirmed values of the mutual inductance M_{ab} , capacitances and resistances.

[0033] In the exemplary method 90, having obtained the mutual inductances M_{ab} between every distinct pair of coils in the integrated layout 38, an integrated layout equivalent circuit model 45 may be created that includes the mutual inductances M_{ab} between all the distinct pairs of coil models in the integrated layout 38, as shown in FIG. 5. Performing circuit simulation of the integrated layout equivalent circuit model 45 obtains circuit simulation results (FIG. 10) of the integrated layout equivalent circuit model 45. By tuning one or more of the inductance, resistance and capacitance of one or more of the coil models 40 in the integrated layout equivalent circuit model 45 so that the circuit simulation results (FIG. 10) of the integrated layout equivalent circuit model 45 best fit the circuit simulation results (for example the input impedance) of the theoretical circuit 39, an optimized inductance may be determined for each coil model 40 of each of the coils 31, 32, 33, 34 in the integrated layout 38 (908, FIG. 21).

[0034] From its optimized inductance, the length of each coil 31, 32, 33, 34 is recalculated using the predetermined method mentioned above and the integrated layout 38 of the plurality of coils is then replotted according to the recalculated length of each coil 31, 32, 33, 34 (99, FIG. 21). Optionally, the method 90 may include creating an integrated replotted layout model of the replotted integrated layout using the electromagnetic simulation software, and performing electromagnetic simulation of the integrated replotted layout physical model to obtain electromagnetic simulation results of the integrated replotted layout physical model. The electromagnetic simulation results of the integrated replotted layout physical model may then be compared with the circuit simulation results of the theoretical circuit 39 to confirm the recalculated length of each coil 31, 32, 33, 34.

[0035] To produce the broadband electromagnetic sensor 10, the coil array structure 38 of the sensing portion 20 is fabricated on a printed circuit board 50 according to the replotted integrated layout (910, FIG. 21). The amplifier circuit 20 is also fabricated on the printed circuit board 50 and connected to the coil array structure 38 to form a printed circuit board assembly 51. Notably, in the coil array structure 38 comprising the plurality of coils 31, 32, 33, 34, each coil has a different length from the other coils in the plurality of coils 31, 32, 33, 34. In this way, each coil detects signals having frequencies within its own frequency bandwidth so that

the plurality of coils 31, 32, 33, 34 are together able to detect signals having frequencies within a frequency bandwidth of the sensor 10.

[0036] To verify the working of the broadband electromagnetic sensor 10 for partial discharge detection, a prototype as shown in FIG. 15 was fabricated wherein the sensing portion 20 has a size of 39.6 mm by 52.6 mm and is connected with an amplifier circuit 20 with a SubMiniature version A (SMA) connector. The amplifier circuit 20 is added to improve the detection distance of the antenna array and increase the distance from the power equipment. The prototype thus includes the broadband sensing part 30 and the amplifier circuit 20 part. It has a simple structure and is cost-effective. The conceptual equivalent circuit model of the prototype includes 4th order inductance-capacitance resonant tanks, each one composed of an inductor and a capacitor in series or in parallel.

[0037] To protect the printed circuit board assembly shown in FIG. 8, the printed circuit board assembly may be encapsulated in a plastic shell. In the experimental prototype that was fabricated, the encapsulation had a size of 12.5 mm by 48 mm by 100 mm, as shown in FIG. 16, with openings to allow placement and securing of the prototype with releasable ties on a cable of power equipment from which partial discharge is to be detected.

[0038] The fabricated prototype of the broadband electromagnetic sensor 10 was used to detect partial discharge using an experimental set-up as shown in FIG. 17. The sensor 10 was connected to an FPGA (field programmable gate array) and placed near high-voltage switchgear. The partial discharge of the high-voltage switchgear was detected by the sensor 10 and the collected data was transmitted to a back-end system through the Internet for processing and display. A computer terminal of the back-end system displayed a phase resolved partial discharge (PRPD) of the high-voltage switchgear.

[0039] Sensitivity of the prototype sensor 10 was verified by varying its position from the partial discharge source. In the tests conducted, using a calibrator as the partial discharge source with 5 pC, the prototype sensor 10 was placed near a cable of the calibrator and the detected partial discharge was obtained and shown on the screen of an oscilloscope. A commercial HFCT sensor was similarly placed around the cable and used to detect the partial discharge from the calibrator. Compared with the commercial HFCT sensor, the oscilloscope result obtained by the prototype sensor has similar pattern but has a larger magnitude, as shown in

FIG. 18. When the prototype sensor 10 was placed 1 meter away from the power equipment for detection, the prototype sensor 10 was still able to detect the partial discharge, whereas the commercial HFCT sensor fared poorly. Table 1 below shows the results of the tests conducted using the prototype sensor 10 and the commercial HFCT sensor when placed 1 metre away from voltage sources having different applied voltages.

	Prototype sensor		Commercial HFCT Sensor	
Applied Voltage (kV)	2	2.2	2	2.2
Peak-to-peak voltage of detected partial discharge signal (mV)	85	85	1	1

Table 1

[0040] The prototype sensor 10 was also tested on actual high voltage equipment by attaching units of the sensor 10 to multiple cables of the equipment, as shown in FIG. 19. The PRPD results obtained by the sensors 10 are shown in FIG. 20. From the experimental tests conducted, it can be seen that the developed broadband electromagnetic sensor 10 comprising four planar coils with additional capacitors as produced using the above-described method 90 performs with a wideband feature and is able to detect partial discharge even at a distance from the high voltage equipment.

[0041] While there has been described in the foregoing description exemplary embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations in details of design, construction and/or operation may be made without departing from the present invention. It will be appreciated that many further alterations, modifications and permutations of various aspects of the described embodiments are possible that fall within the spirit and scope of the appended claims. For example, while the coil array structure shown in the figures has a generally rectangular shape, the coil array structure may have other configurations such as circular, three-dimensional or any other arbitrary shapes.

[0042] Throughout this specification and the claims which follow, unless the context requires otherwise, the word “comprise”, and variations such as “comprises” or “comprising”, will be

understood to imply the inclusion of a stated integer or group of integers or steps but not the exclusion of any other integer or group of integers. The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that that prior publication (or information derived from it) or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

Claims

1. A method of producing a broadband electromagnetic sensor, the broadband electromagnetic sensor comprising an amplifier circuit in connection with a sensing portion, the sensing portion comprising a coil array structure of a plurality of coils wherein each coil is able to detect signals having frequencies within its own frequency bandwidth and wherein the coil array structure is able to detect signals having frequencies within a frequency bandwidth of the broadband electromagnetic sensor, the method comprising the steps of:
 - (a) representing the sensing portion as a theoretical circuit wherein each coil of the plurality of coils is represented by a theoretical inductor having a theoretical inductance, and performing circuit simulation of the theoretical circuit to obtain circuit simulation results of the theoretical circuit and to obtain the theoretical inductance of each coil;
 - (b) calculating a length of each coil from its theoretical inductance using a predetermined method, and plotting an integrated layout of the plurality of coils according to the calculated length of each coil;
 - (c) creating a coil model of each coil in the integrated layout using an electromagnetic simulation software, and performing electromagnetic simulation of the coil model to obtain electromagnetic simulation results of the coil model;
 - (d) creating a coil equivalent circuit model of each coil model wherein each coil model is represented as an inductor provided in parallel connection with a capacitor and in series connection with a resistor, and performing circuit simulation of the coil equivalent circuit model to obtain circuit simulation results of the coil equivalent circuit model and to determine for each coil model its inductance, resistance and capacitance when the circuit simulation results of the coil equivalent circuit model best fit the electromagnetic simulation results of the coil model;
 - (e) creating a two-coil model of two coils in the integrated layout using two coil models that had been created in step (c), and performing electromagnetic simulation of the two-coil model to obtain electromagnetic simulation results of the two-coil model;
 - (f) creating a two-coil equivalent circuit model of the two-coil model using two coil equivalent circuit models that had been created in step (d), wherein the two-coil equivalent circuit model includes a mutual inductance in the two-coil model, and performing circuit simulation of the two-coil equivalent circuit model to obtain circuit simulation results of the two-coil equivalent circuit model and to determine the mutual

- inductance in the two-coil model when the circuit simulation results of the two-coil equivalent circuit model best fit the electromagnetic simulation results of the two-coil model;
- (g) repeating steps (e) and (f) for every distinct pair of coils in the integrated layout to determine the mutual inductance between every distinct pair of coils in the integrated layout;
 - (h) creating an integrated layout equivalent circuit model using all the coil equivalent circuit models that had been created in step (d), wherein the integrated layout equivalent circuit model includes the mutual inductances between every distinct pair of coils in the integrated layout, and performing circuit simulation of the integrated layout equivalent circuit model to obtain circuit simulation results of the integrated layout equivalent circuit model and to determine for each coil model its optimized inductance when the circuit simulation results of the integrated layout equivalent circuit model best fit the circuit simulation results of the theoretical circuit;
 - (i) recalculating the length of each coil from its optimized inductance using the predetermined method and replotting the integrated layout of the plurality of coils according to the recalculated length of each coil; and
 - (j) fabricating the coil array structure on a printed circuit board according to the replotted integrated layout.
2. The method according to claim 1, wherein the theoretical circuit in step (a) comprises a ladder structure of a bandpass filter wherein each element of the ladder structure comprises one of the theoretical inductors in electrical connection with a theoretical capacitor, and wherein each element is configured according to a preselected response type.
 3. The method according to claim 2, wherein the preselected response type is one of: a Butterworth response, a Chebyshev response, and an elliptic response.
 4. The method according to any one of claims 1 to 3, further comprising, immediately after step (h), creating a circuit validation model of the two coils that includes the confirmed mutual inductance between the two coils and performing circuit simulation of the circuit validation model to obtain circuit simulation results of the circuit validation model, wherein fitting of the circuit simulation results of the circuit validation model with the circuit

simulation results of the two-coil equivalent circuit model confirms the mutual inductance between the two coils.

5. The method according to claim 4, wherein the circuit validation model of the integrated layout comprises a T-type circuit.
6. The method according to any one of claims 1 to 5, wherein the electromagnetic simulation results and the circuit simulation results include variation of input impedance and scattering parameter with frequency.
7. The method according to any one of claims 1 to 6, further comprising fabricating the amplifier circuit on the printed circuit board and connecting the amplifier circuit with the coil array structure.
8. The method according to any one of claims 1 to 7, further comprising, after step (i), creating an integrated replotted layout model of the replotted integrated layout using the electromagnetic simulation software, performing electromagnetic simulation of the integrated replotted layout physical model to obtain electromagnetic simulation results of the integrated replotted layout physical model, and comparing the electromagnetic simulation results of the integrated replotted layout physical model with the circuit simulation results of the theoretical circuit to confirm the recalculated lengths of each coil.
9. A broadband electromagnetic sensor comprising:
 - an amplifier circuit having at least 26 dB gain through its bandwidth; and
 - a sensing portion comprising a coil array structure of a plurality of coils, wherein each coil has a different length from other coils in the plurality of coils and detects signals having frequencies within its own frequency bandwidth, such that the plurality of coils are together able to detect signals having frequencies within a frequency bandwidth of the sensor, and wherein the frequency bandwidth of the sensor ranges from around 1 MHz to 100 MHz, such that the sensor is able to detect partial discharge from high voltage equipment without being in physical contact with the high voltage equipment.

10. The broadband electromagnetic sensor according to claim 9, wherein the coil array structure is provided as an integrated layout on a printed circuit board, and wherein the integrated layout is optimized to minimize area of the printed circuit board required to support the coils.
11. The broadband electromagnetic sensor according to claim 9 or claim 10, wherein each coil can be represented by an equivalent circuit model comprising a capacitor provided in parallel connection with an inductor and the inductor provided in series connection with a resistor.
12. The broadband electromagnetic sensor according to any one of claims 9 to 11, wherein the sensing portion can be represented by an equivalent circuit model that incorporates mutual inductance between every distinct pair of coils in the coil array.
13. The broadband electromagnetic sensor according to any one of claims 9 to 12, wherein the coil array structure comprises one of: a rectangular shape, a circular shape, a three-dimensional structure.
14. The broadband electromagnetic sensor according to any one of claims 9 to 13 produced by the method according to any one of claims 1 to 8.