MODELLING AND IMPLEMENTATION OF A NOVEL HIGH-FREQUENCY GENERATOR CONFIGURATION FOR HIGH-VOLTAGE APPLICATIONS

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Abstract:

In recent days with an increase in power demand the distribution as well as generation of an electrical energy needs an innovative and automated technologies by using power electronic circuits with higher amount of voltage at various distinct frequencies. These different types of generated voltages require better insulating materials and the corresponding components of the circuits with the help of transformer couplings. To achieve this we need to analyze the characteristics of dielectric medium of the materials and also the corresponding electric insulation properties with a high-voltage and high-frequency generator with the help of the condition of resonance where impedance is equal to resistance up to 50 kV maximum value in a frequency range of 1 kHz up to 100 kHz was presented. A specific separate coil is designed with the usage of a suitable insulating medium with an ensured dielectric strength of the generator. The combination of both conventional DC and AC high voltage test modules with the exposed generator allows the generation of superimposed voltages for various different frequencies and amplitude values. First measurements of breakdown voltages in air at higher frequencies are presented.

Keywords: Renewable energy sources (RES), HV (High Voltage), LV (Low Voltage).

1 INTRODUCTION:

In recent days with an increase in structural electric power grids structural changes from centralized grid circuits to a decentralized grid with the help of non conventional energy sources like solar PV power and wind power plants requires novel automated material requirements for their respective electrical systems and equipments. These circuits include compact size components for establishing micro power grids. So the manufactures of these micro grid applicants produces very less amount of power having low number of consumers and also they had very small energy storage components which requires intelligent and efficient coupling with each other circuits. [1]. with an advancement of Power electronic area researchers are interested in power electronic components and assemblies because of its compact size and low cost so in these components are extensively used for coupling circuits by the respective electrical consumers and producers in micro grid applications.

The very important advantage of usage of semiconductor components compared to available conventional energy conversion technologies are these power electronic components operates at high power density value with flexible in operation. This opportunity of flexibility in the flow of energy provides a good possibility to couple grids easily and the corresponding components operate at different multi voltage levels and also at different higher frequencies efficiently (DC&AC 50 Hz, 100 Hz, and 200 Hz). The discussed high-frequency-transformers to couple the power electronic systems further can be made more compact in size [2]. In addition to the above a very high-transferable power is possible with the help of series and parallel connections of modules.

With the above mentioned development and advancements in power electronics the manufactures are interested in power transformers which are in compact size with low cost. These power transformers are mainly used for high frequency and high voltages applications. The discussed transformers also provides in regards to the magnetic transfer and dielectric strength [2, 3]. This article mentions a novel high-frequency and high-voltage generator which develops a higher voltage up to 50 kV peak with a frequency range of 1 to 100 kHz for normal dielectric investigations of various materials and high voltage tests of different equipments. A test object with a capacity up to 1.9 nF can be stressed with a pure sinusoidal high frequency high voltage. In this article we also present the possibilities and chances of the high-frequency high-voltage generator interconnections with other conventional high voltage test systems. These systems will generate superimposed voltages.

2 DESIGNS AND PRINCIPLE OF OPERATION:

2.1 Circuit operation:

The novel high-frequency& high-voltage generator is mainly an electrical configuration operates at resonant condition and takes the excitation from resonance converter on the LV side of the transformer. Here an inductive coupler and high voltage capacitances generate the high frequency test voltage as a constant sinusoidal high voltage. Figure 1 represents the the schematic diagram of principle of operation. In the mentioned topology capacity C_{rc} of the resonance converter, combined with the inductance L_1 of the inductive coupler, set up a low voltage series resonant circuit with the current i_{rc} up to 50 A. Other mentioned inductance L_2 of the inductive coupler is combined with the capacitance C_{HV} set up a parallel resonant circuit where the generated high voltage.

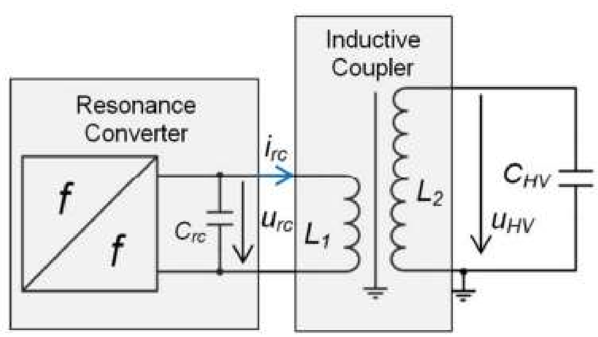

Figure 1: High Voltage high frequency topology

In the above represented circuit a ferrite core material inductive coupler has been used for the transmission of an electrical energy as well as controlling of magnetic flux. Here the current magnitude value is i_{rc} and thus the corresponding voltage is u_{HV}. The respective voltage can be controlled by using the value of duty pulse or by using the common DC link voltage. Similarly respective frequency of the current i_{rc} could be adjusted to the corresponding resonant point within a range from 1to 100 kHz. At resonant condition, the capacitive reactance equals the inductive reactance and only the impedance is the resistance. At this resonant condition, the current Series resonant current value i_{rc} and the parallel resonant voltage value uHV are in sinusoidal shape and are disposed by angle of $\pi/2$. Figure 2 shows the respective current and voltages wave forms for a resonant condition at frequency of 48 kHz.

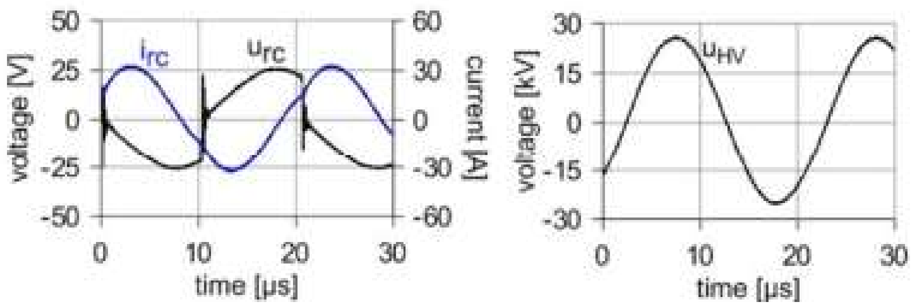

Figure 2: Current and voltage waveforms

The described principle of operation of the generator fives the following advantages.

1. It generates a very high frequency high voltage value approximately pure sinusoidal test voltage in the frequency value of 1 to 50 kHz up to 30 kV maximum.
2. Here by using the resonance principle operation the generation loses for generating a constant single frequency sinusoidal voltage losses are minimized.
3. By using this module we can easily adjust the value of resonant frequency with the help of high voltage capacitors.
4. The frequency is done at resonant value and also the test voltage magnitude.
5. Here the losses are minimized by using high grade copper material.

2.2 Parasitic components:

By using the combination of the discrete components in the configuration the basic principle of the circuit is described using parasitic elements. These parasitic elements normally operate at resonance frequency. The below Figure 3 represents an equivalent circuit where the operated parasitic inductances (supply and distribution of the magnetic coupler and stray inductance of the inductive coupler) which are mentioned in the inductor L_{stray} represented on the LV Side and the acting parasitic capacitances are represented on the HV side

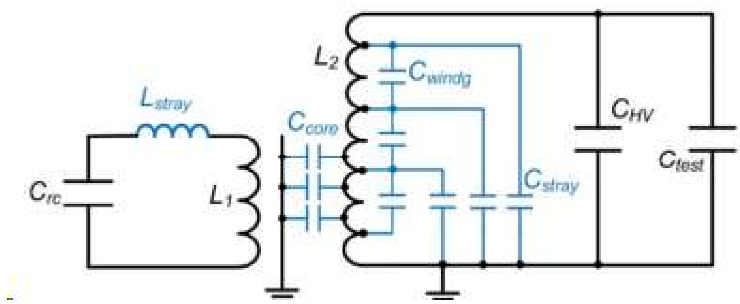

Figure 3: Resultant circuit of high-frequency high-voltage resonant circuit with parasite elements

From the above configuration the resonant frequency can be defined as

$$f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}} \qquad (1)$$

Where: $L = f(L1, L2, L_{stray})$ $C = f(CHV, C_{test}, C_{rc}, C_{stray}, C_{windg}, C_{core})$

The equivalent value of the capacitance of the resonant circuit is given by the HV side capacitor and the resonance capacitor C_{rc} and also in combination of other equivalent capacitance values. These values include the amount of ground capacitances C_{stray}, the capacitance between the secondary side coil and the core C_{core} and the capacitances of the windings C_{windg} to each other in the coil L_2.

With all the above discussed elements the high-frequency-high-voltage generator phenomena is a self-resonance condition. These parasite components present the upper limit frequency of the resonant circuit. By adjusting the value of the C_{HV} the resonant frequency can be shifted. Figure 4 shows the operating region of the high-frequency high-voltage generator and the self-resonance point.

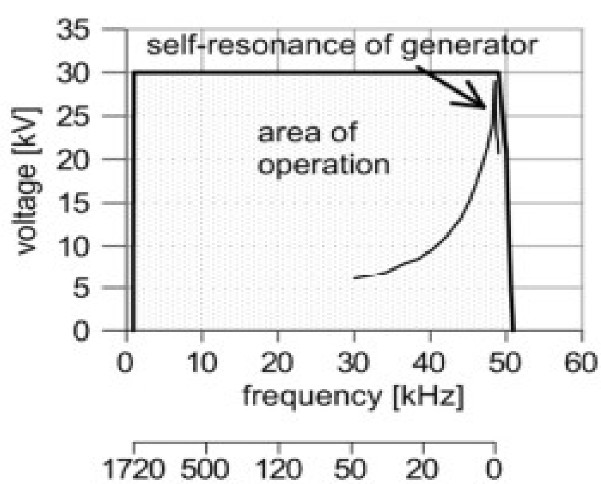

Figure 4: Operating region of generator with self-resonance condition and load capacitance

2.3 Inductive coupler:

In order to join the HV side with LV side an inductive coupler is developed. Generally the laminated iron core is used in normal transformers. This iron core is not generally preferred because of high core losses and heating effects at higher frequencies. Therefore in this we are considering an iron core made by ferrite material. The schematic of the core and coil is presented in Figure 5.

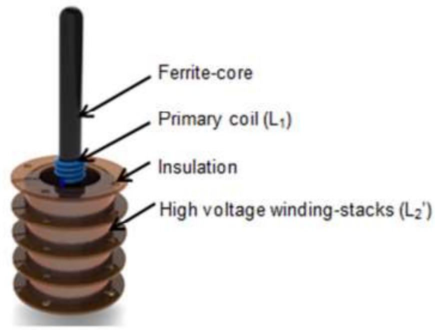

Figure 5: Schematic of inner part of the inductive coupler

3. ELECTRICAL INSULATION:

3.1 Coaxial constructions for electrical field control:

The schematic structure of the generator is obtained from the condition of optimum field. Consider for the purpose of optimization of electric field we need to assume the inner of the secondary coil having a voltage of U_{HV}. The bottom is manufactured with ferrite material. Because of its resistivity i.e 10 Ωm the outer core voltage value does not equal to the ground potential but having some voltage. The optimized raddi is given by the following equation

$$\left.\frac{r_{outer}}{r_{inner}}\right|_{E_{min}} = \frac{r_{L2}}{r_{core}} = e = 2{,}7 \qquad (2)$$

Table 1 shows the chosen radii and the ratio of the coaxially arranged components.

Table 1: Radii and ratio of radii

Core radius r_{core}	Inner coil radius r_{L2}	r_{L2}/r_{core}
11 mm	30 mm	2,72

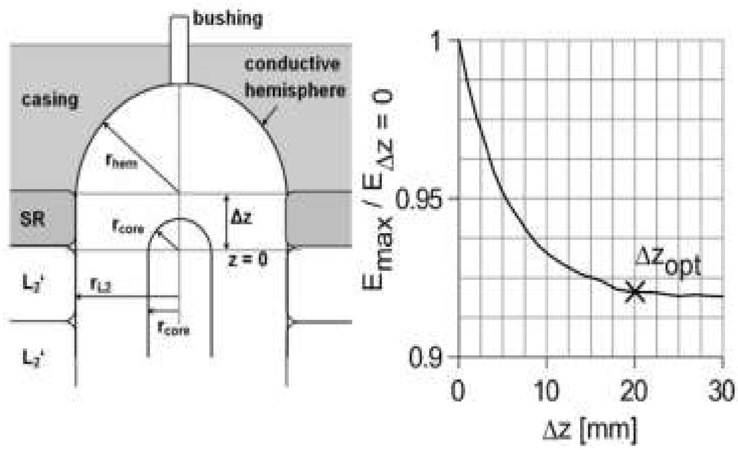

Figure 6: Cross section view of inductive coupler

The above circuit shows the schematic diagram of the inductive couple configuration. The top view of the L2 coil is created by using a module called as inserted shield ring (SR) for creating the electrical field control. The top of the ferrite core possess discharged so to protect from the ferrite top core discharges the structure of the core is rounded to a hemisphere with the radii core. A conductive hemisphere in the casing forms the counter electrode on the high voltage side. The hemisphere has the same radius rhem as the inner radius rL2 of the high voltage coil L2. The optimal distance Δz between the casing with the conductive hemisphere and the coil L2 has to be found, so that the field strength is minimized on the ferrite core. Figure 6 (right) shows the geometrical sweep as a result of FEM simulation with Consol Multi physics

3.2 Effects of eddy currents:

Because of the high frequency magnetic field, eddy currents have to be under special attention. In round conductive components, which are permeated by this high frequency magnetic flux, eddy currents appear. These flow at the surface (skin effect) and heat them. This means additional losses and heating in the system. The design of the field closure at the top of the coil L2 must be adapted to avoid eddy currents. For this reason, the shield ring and the conductive hemisphere in the casing are specially constructed. The shield ring is made of a synthetic fiber reinforced epoxy with a conductive coating. The conductive coating is fragmented in several stripes, so no eddy current can flow around the circumference. The casing, in which the hemisphere is milled, is made by a thermoplastic polymer. As well, the hemisphere has conductive coated segments and space between them to prevent the flow of eddy currents. 3.3 Electrical insulation of the high voltage coil the high voltage coil has two main tasks. On the one hand, it is part of the inductance which effects on the resonant frequency and on the other hand, it is the coil of the inductive coupler which is permeated by the magnetic flux induced by the current i_{rc}. In conjunction with the coil L_1 the coil L_2 must have a high winding ratio for good electrical induction. That means a high number of windings in the area of magnetic main flux. Several layers of turns at the height of the ferrite core are necessary. In discrepancy to this, a small number of turns and a small inductance are necessary for a high frequency range and high upper limit frequency. In addition to the inductance also the parasitic capacitances between the windings affect the upper limit frequency. To ensure the dielectric strength of the high voltage coil and to achieve a small height, a special winding technique is used. The high voltage coil consists not only of a single multi-layer wound coil, but the interconnection of multiple winding-stacks, which have a layer of windings. The entire coil is an interconnection of ten winding stacks. Figure 7 shows the schematic design of the windings, shown by the two upper winding-stacks.

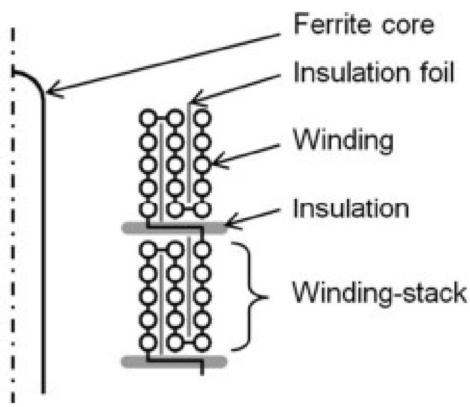

Figure 7: Winding scheme

Individual winding layers of a stack are insulated with a foil to each other. The windingstacks are insulated with a disc to each other. An insulation disc creates the dielectric strength between the several winding-stacks and the mechanical tension of the winding-stacks to each other.

3.4 SF_6 gas for electric insulation:

To ensure a reliable and partial discharge free generator, the inductive coupler is encased by SF6 atmosphere, additionally. A pressure-tight casing is around the coil structure. Gas pressure and temperature controls are installed and evaluable.

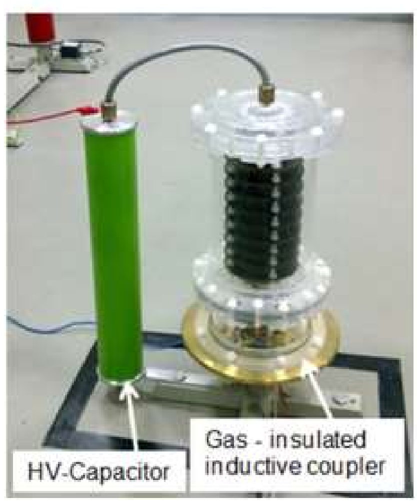

Figure 8: High-frequency high-voltage generator with gas insulated inductive coupler

Uniform heat dispersal in the gas volume inside the casing (due to heating of the ferrite core and the skin effect in wires) is achieved by circulating the gas through a fan. The volume of gas is drawn by the fan from inside the coaxial structure, contrary to the natural convection and passes outside the high voltage coil up again. For the gas exchange on the volume outside the coil L2 to the internal volume the shield ring is slit. The metallic ground plate of the casing serves to be the refrigeration unit to the generator ambient air. Thus, a local overheating (hot spots) of components will be avoided.

4 Generable Test Voltages:

4.1 High frequency test voltage:

The presented generator produces a high frequency high voltage up to 30 kV and up to 50 kHz. It is a constant pure sinusoidal test voltage. The frequency and amplitude can be adjusted by the resonance converter. An example of this test voltage is given in Figure 9.

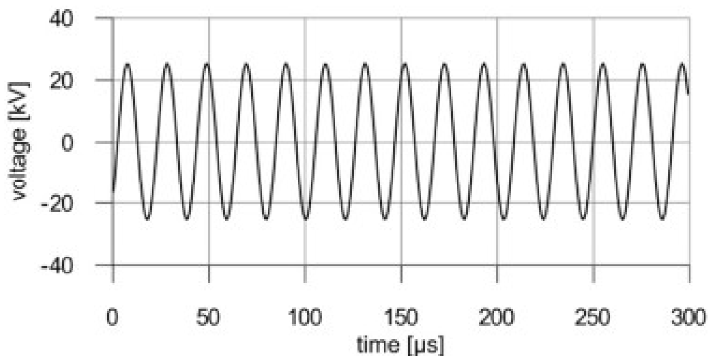

Figure 9: high frequency high test voltage at 48 kHz

4.2 Superposition of a 50 Hz test voltage with a high frequency test voltage:

For recreating electrical real stress for insulation systems as in power electronic cascade assemblies occurs, mixed voltage waveforms has to be generated. To this end, the high-frequency high-voltage generator was connected with a conventional high voltage 50 Hz AC test transformer. The equivalent circuit is shown in Figure 10. For decoupling, a 200 pF capacitor is inserted which has high impedance for the 50 Hz alternating current. A 400 kΩ resistor provides the current limit of the test transformer. An example of a produced mixed form voltage of two AC voltages with different frequency is shown in Figure 11.

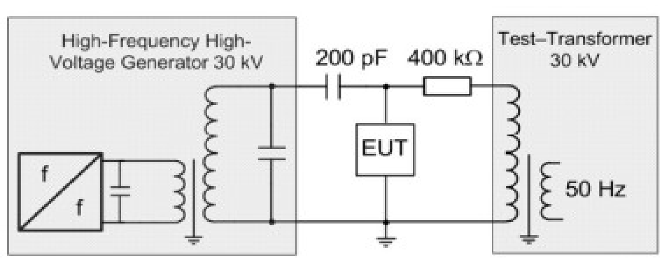

Figure 10: Equivalent circuit for interconnection of the high-frequency high-voltage generator and a 50 Hz test transformer

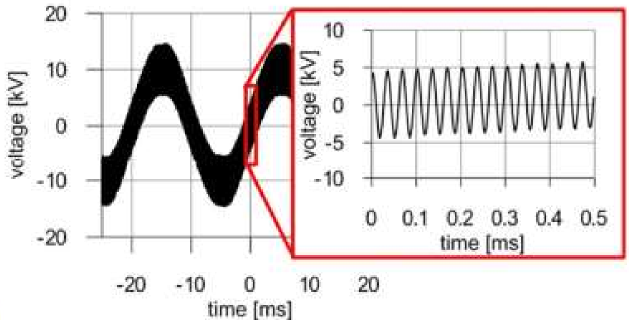

Figure 11: Generated superimposed voltage of 50 Hz and 30 kHz alternating voltages

4.3 Superposition of a DC test voltage with a high frequency test voltage:

For interconnection of the high-frequency high-voltage-generator with a Greinacher-circuit, the direct current is decoupled by a 20 nF capacitor which represents an infinitely high resistance for direct currents. The higher frequency voltage of the generator is decoupled with a 500 mH high voltage coil, which represents high impedance for high frequency alternating current. Figure 12 shows the equivalent circuit diagram and Figure 13 an example of a generated superimposed mixed voltage.

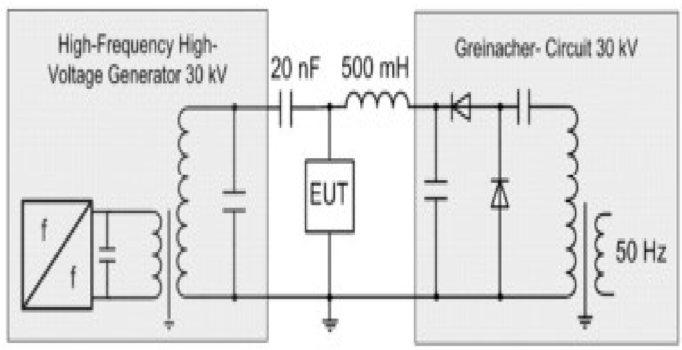

Figure 12: Equivalent circuit for interconnection of the high-frequency high-voltage generator and a Greinacher-circuit

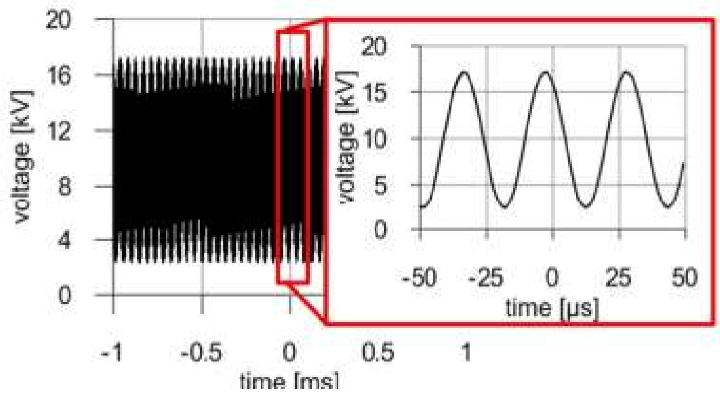

Figure 13: Generated superimposed voltage of DC and 32 kHz alternating

5 First Tests-Breakdown Voltages In Air At 40 KHz:

First dielectric studies were carried out in a homogeneous field with a spark gap in air and a pure sinusoidal high frequency alternating voltage. The electrical breakdown in air is investigated and well known at frequencies up to MHz range by XVII International Symposium on High Voltage Engineering, Hannover, Germany, August 22-26, 2011 calculations and measurements. The lowering of breakdown voltages in air up to 20 % can be expected at a certain critical frequency and a certain critical gap distance [4]. Results of measurements [4, 5, and 6] show a constant breakdown voltage at higher frequencies with a pre-ionized spark gap at short gap distances. This suggests the same breakdown voltages at frequencies from 50 Hz to about 1 MHz below any critical frequency in relation to a critical gap distance. At first tests at a frequency of 40 kHz higher breakdown voltages than static breakdown voltages have been measured. Figure 14 (left) shows the comparison of measured breakdown voltages Ub at a frequency of 50 Hz and 40 kHz in a homogeneous field. The breakdown voltage at 40 kHz is up to 15 % - 25 % higher than the static breakdown voltage at distances of 0.5 mm to 6 mm. The breakdown voltages may be higher than the static breakdown voltages, because of the time dependent processes which lead to electrical breakdown in gases. Figure 14 (right) shows an oscillogram of an electrical breakdown at 29 kV at a gap distance of d = 7 mm.

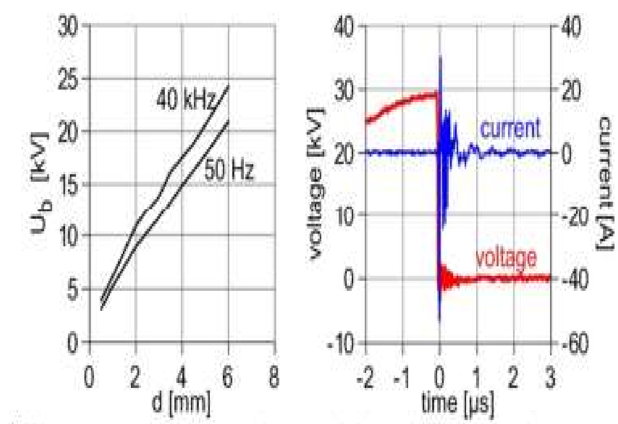

Figure 14: Comparison of breakdown voltages at 50 Hz and 40 kHz

Over spark gap distance (left) and breakdown voltage and current over time (right) for one distance, 30 measurements were accomplished with polished, cleaned sphere copper electrodes (diameter = 5 cm) without any preionization. The measured values are converted to normal atmospheric conditions with the correction factors for pressure and temperature.

6 Conclusions:

The presented paper shows the build-up and the principle of a high-frequency high-voltage generator based on resonance principle. It generates a high voltage with amplitude up to 30 kV in a frequency range of 1 kHz to 50 kHz. The power supply is provided by a resonance converter. An inductive coupler, which separates the high voltage parallel resonant circuit to the low voltage series resonant circuit supplies galvanically isolation. Because of the applied resonance principle the generator produces loss minimized a constant sinusoidal high voltage. Insulating materials and systems can be stressed with this higher frequency high voltage. The influence of parasitic elements is shown as well as the optimal field design of the generator. The electrical strength of the high voltage coil is ensured by a special winding technique. For a partial discharge free operation insulation gas SF6 is useful. Furthermore, the interconnection of the highfrequency high-voltage generator with conventional test systems (test transformer: AC 50 Hz and Greinacher-circuit: DC) is presented. That enables the generation of voltage waveforms of superimposed different frequencies and potentials. First tests show the dielectric breakdown voltages of a spark gap at 40 kHz compared to the static breakdown voltages in air. The breakdown voltages are up to 15 % - 25% higher at 40 kHz to the static breakdown voltages.

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