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A NEW HV-SERIES RESONANT CIRCUIT FOR DIELECTRIC TESTS

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ABSTRACT

Contrary to the well known actual technique, this HV-series resonant circuit is excited by a continuously variable frequency. As the reactor used within this circuit is designed for a constant inductivity, the dimensions and the weight can be minimized. Therefore, one achieves the opportunity to build up the lightest and smallest ac-power supply for dielectric testing of big capacitances in the frequency range of a few ten cycles up to some hundred cycles. The operating characteristics of such a circuit are shown; some main aspects of the design of the exciter supply and the HV-reactors are discussed. Test results for a 200 kV/6 A reactor unit are presented, which will be used for a 750 kV/6 A series resonant circuit.

1. INTRODUCTION

The difficulties arising by power frequency dielectric testing of capacitances with more than a few 10^{-9} F are well known: testing transformers are usually rated for short time currents of not more than 1 to 2 A/MV or capacitive loads of about 3 to 6 nF for 50/60 Hz. The weight of these transformers, though kept as small as possible, is relatively big and is typically about 10 to 20 kg/kVA, not including the necessary regulating and control equipment. Much less capacitive loads than the nominal ones are permissible for higher frequencies. Therefore, the application of testing transformers is essentially restricted to HV-laboratories and it is difficult to use them for field testing, if the test voltage is higher than a few hundreds of kilovolts.

Resonant circuits for the generation of high ac-test voltages are therefore increasingly used for testing of big insulating systems with larger capacitance values, as HV-cables or SF_6-insulated switchgears (GIS). Whereas a parallel resonant circuit, in which capacitive load is shunted by a HV-reactor, has some advantages if the resonant frequency of the circuit is not stable, since the active power of the circuit is injected by a HV-testing transformer of small rating, the series resonant (SR) technique is often used today [1]. This usual SR-circuits are fed by an exciter supply operating with fixed power frequency, so that a continuously variable reactor is necessary to adjust the resonance frequency of the circuit. Though these steel core HV-reactors with variable air gaps cannot be designed in such a way, that the magnetic field energy is produced by a minimum amount of iron and copper, the specific weight of such oil insulated reactors can be reduced to about 3 to 6 kg/kVA for 60 Hz [1], which is less than stated in [2].

This paper shows that a further reduction of size and weight is possible, if a SR-circuit is designed with reactors of constant inductance so that the supply frequency has to be adjusted according to the resonance frequency. The operating characteristics of such circuits will offer so many outstanding features that the disadvantage of having a powerful HV-testing equipment with not fixed power frequency is acceptable.

For GIS the necessity of an ac-dielectric test at site was adopted by many publications [2, 3, 4] due to the fact that this test effectively considers the influences of particle contaminations. Site dielectric tests for HV-cables or large power generators are also a wide field of application.

2. CHARACTERISTICS OF SR-CIRCUIT WITH VARIABLE FREQUENCY

Fig. 1 shows the scheme of the whole SR-test circuit. The capacitance C represents the test specimen and other shunt capacitances (capacitor voltage divider, capacitance of reactor windings), L_n is the nominal inductance of all reactor units.

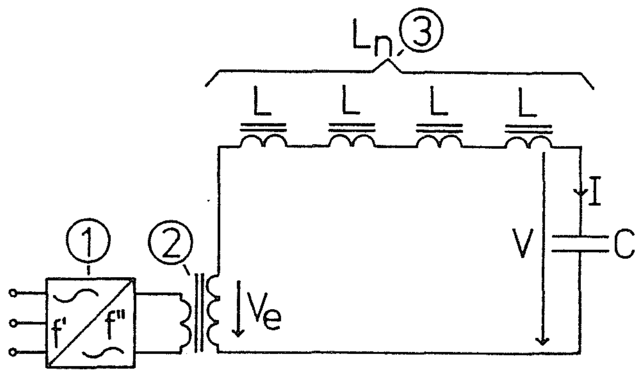

Fig. 1: Schematic diagram of SR-test circuit

1: Exciter supply: frequency converter
2: Exciter transformer
3: Reactor or reactor units

The exciter voltage V_e is always small in comparison to the voltage V across the test object, as the quality factor $Q = L_n/R = 1/RC$ is high in a wide range of frequencies $f = \omega/2\pi$ (R represents all losses in the circuit). The design criteria and operating characteristics are derived from the known theory of a SR-ciurcuit. As the circuit is alway operated at or very close to the resonance frequency

$$f = f_r = 1/2\pi\sqrt{L_n C} \qquad (1)$$

the nominal inductance L_n will be choosen from a nominal capacitance C_n, which is the highest capacitance that can be tested with the highest rated voltage V_n and a nominal frequency f_n, the lowest frequency within the rated voltage. Therefore,

$$L_n = \frac{1}{(2\pi)^2 f_n^2 \cdot C_n} \quad (2)$$

A further criterium for the reactor is the maximum or nominal current $I = I_n$, which either overheats the coil or saturates the steel core. As $R \ll \omega L_n$, I_n may directly be drived from the voltage drop across L_n,

$$I_n = \frac{V_n}{2\pi \cdot f_n \cdot L_n} \quad (3)$$

or from the fact, that for all frequencies or every cycle the magnetic energy in the reactor is equivalent to the electric energy stored within the test specimen (see also equ. (11)):

$$I_n = V_n \sqrt{\frac{C_n}{L_n}} \quad (4)$$

For test objects with capacitance values C different from C_n, the resulting test frequency f, the permissible test voltage V and resultant or acceptable current I is now from interest. All these values can be standardized with the nominal values, and in this way the following fundamental operating characteristics for the circuit are given:

According to equ. (1), for a fixed inductance L_n the test frequency f will be

$$\frac{f}{f_n} = \sqrt{\frac{C_n}{C}} \quad (5)$$

For $C \leqq C_n$, the reactor L_n can be used up to the full rated voltage V_n. For $C > C_n$, the current I is given by:

$$\frac{I}{I_n} = \frac{V}{V_n} \cdot \sqrt{\frac{C}{C_n}} \quad (6)$$

Equ. (6) shows that the circuit can easily be used also for testing of even much bigger capacitances. As the reactor operates for $f < f_n$ as well with the nominal current I_n as for the nominal frequency, equ. (6) claims for the following reduction of the test voltage with $I = I_n$:

$$\frac{V}{V_n} = \sqrt{\frac{C_n}{C}}\,; \quad \text{for } \begin{matrix} C \geqq C_n \\ f \text{ acc. equ. (5)} \end{matrix} \quad (7)$$

The real limitations in testing very large test specimens with lower voltages than V_n are given by the reduction of Q for too low frequencies (see Fig. 6), and the frequency for which the exciter transformer saturates. As this transformer, however, feeds the losses into the circuit only, it can easily be dimensioned for the full excitation voltage V_e for $f < f_n$.

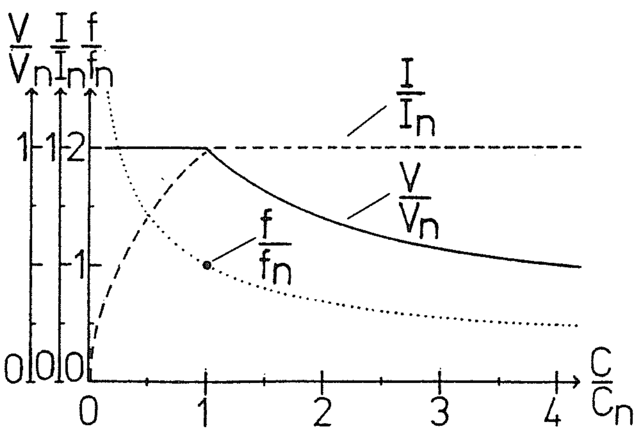

Fig. 2: Operating characteristics of circuit acc. to Fig. 1

Fig. 2 shows these normalized characteristics according to equ. (5), (6) and (7). The diagrams are based upon Fig. 1, in which the inductance L_n is defined for one or more reactor units. The big flexibility of the circuit is obvious if L_n is splitted up into a number of equal elements which can be cascaded as well as switched in parallel.

3. DESIGN OF A 750 kV SR-CIRCUIT

Due to the size of a GIS, a load capacitance of about 10 nF must be assumed for site testing. The necessary test voltages are usually lower than the rated power-frequency withstand test voltages for acceptance testing. Therefore a test voltage level of about 700 kV seems to be acceptable for testing of 420 kV apparatus. For safety reasons one decided to build up a SR-circuit for 750 kV. In order to be able to test the GIS including magnetic voltage transformers, the nominal frequency f_n was raised to more than 100 c/s.

A) The reactor

A series or parallel connexion of several unit reactors has the same quality factor, nominal frequency and frequency range as one unit reactor has. Therefore it is of utmost importance to design one unit reactor as best as possible. Many variables had to be considered during the design of the HV-reactor L_n. By fulfilling the following three prerequisites, the major variables could be rationalized:

a) Does the reactor become particularly light at high or low nominal frequencies?

b) Bar core or gapped iron core magnetic circuit?

c) How can the quality factor be optimized?

To a): The reactive power balance of a SR-circuit reveals that the reactors have to compensate the full reactive power of the test specimen.

$$Q_L = Q_C = V^2(2\pi f)C \quad (8)$$

This shows that at the resonant frequency f, the capacitive reactive power Q_C and the inductive reactive power Q_L are of the same absolute value and correspond with the power of the test specimen C at the frequency f. Q_C is increasing with the frequency, i.e. the nominal power of the reactor units would be very small at low frequencies and viceversa. The seeming advantage of the small nominal frequency of the reactor elements, however, goes lost, considering that the maximum induced voltage in a reactor is linearly dependent upon frequency. The maximum induced voltage V_i is reached by the saturation current I_o:

$$V_i = (2\pi f)LI_o \quad (9)$$

As V_i is about equal to V, the induced voltage must be increased for low frequencies by increasing L or the number of windings. As the charging current of C for constant voltage decreases also linearly with frequency, the increase of the windings-number with constant current density is possible. That means to the resonant circuit that the balance of the reactive power as shown in equ. (8) results in equal reactor sizes in a wide frequency range. This equalization confirms also the well known fact that the field energy $V^2C/2$, which is stored in the capacitor C, is converted to the magnetic field energy $I^2 \cdot L/2$ for oscillating reasons. The maximal values are given by

$$Q_L = Q_C = V^2(2\pi f)C = I_o^2(2\pi f)L_n \quad (10)$$

or

$$\hat{V}^2 C = \hat{I}_o^2 \cdot L_n \quad (11)$$

Equ. (11) shows also, that the size of the reactor is not depending on its nominal frequency because the only criterion is its energy content. For $f > f_n$, or $C < C_n$, this energy content cannot be used as V is limited by insulation problems (see equs. (11), (5) and (6)).

To b): Constructing a reactor, the following two principles are valid:

- The storage of energy takes place in the air gaps.
- The volume of the air gap, the power at a certain frequency and the energy content increase with the 4th power of the linear reactor dimensions.

The first principle indicates that e.g. a transformer cannot be used as reactor since the storage of energy in an air gap is missing. The second principle shows that better power-weight ratios can be achieved by big reactors as the weight increases only with the volume or the 3rd power, whereas the electrical power is increasing with the 4th power. This principle contains also important informations for the comparison of a cylindrical bar core or gapped iron core - or essentially closed - magnetic circuit: The "closed" magnetic circuit is able to adapt in any power range to the required volume of the air gap. Depending on construction, the equivalent air gap of a bar core is big. It could be reduced by extending the ends of the core, but this requires too much iron. The second principle says that only big reactors do have relatively large air gaps, i.e. open magnetic circuit are only useful when producing high power. Since one saves, however, much weight of iron, the power-weight ratio of one reactor with a bar core magnetic circuit is much lower than that with a "closed" manigetic circuit.

The quantitative calculation reveals that the energy of the desired unit reactor is so high that it renumerates to apply a bar core magnetic circuit. Informations about the calculation of such cores are given in [7]. Beyond the computer calculation, there is also a quick, precise and cheap procedure which with measurements on a model can be done. By means of the principle of similarity the result can be changed to any similar disposition. As model cores one takes usually ferrites.

To c): The quality factor Q is the quotient from the reactive power in relation to the leakage power. As the leakage power is approximately proportional to the volume and the power increases with the 4th power of the linear dimension, the quality factor of big reactors is high as long as the frequencies are not too low (small reactive power) or not too high (high losses in the iron).

Due to this considerations a reactor unit was developed for a modular design of the whole 750 kV SR-circuit, which should be composed of four units.

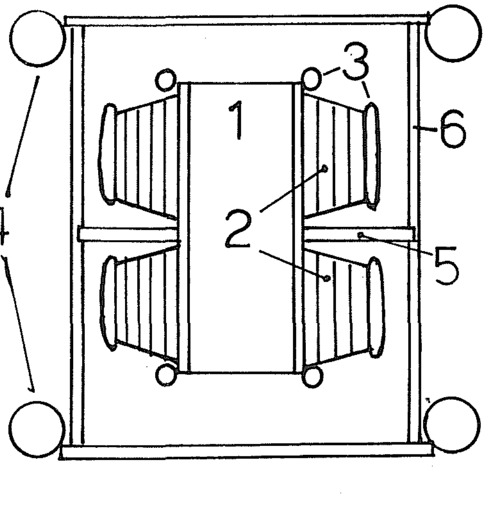

Fig. 3: Outline of reactor unit

Fig. 3 shows an outline of the reactor cross section: A pair of equal HV-coils with layer windings (2) are wound on the radially laminated bar core (1). The coils are connected in series and therefore the core is on half potential, providing an excellent field distribution for the active part. This field distribution is also controlled by internal (3) and external (4) shielding electrodes, the first of which are made of WEIDMANN precompressed and metallized transformerboard. The whole active part is fixed by an insulating plate (5) and suspended within an insulating cylinder (6), filled with transformer oil.

As for bar core construction the magnetic stray flux may influence the inductivity of each reactor if the units are cascaded, and this stray flux still induces eddy currents in metal parts close to the core, the magnetic circuit has been studied and measured by means of a model. Fig. 4 shows this magnetic field and the mutual interference of three cascaded model reactors. The interference results in an increased inductivity of about 5 %, which is tolerable.

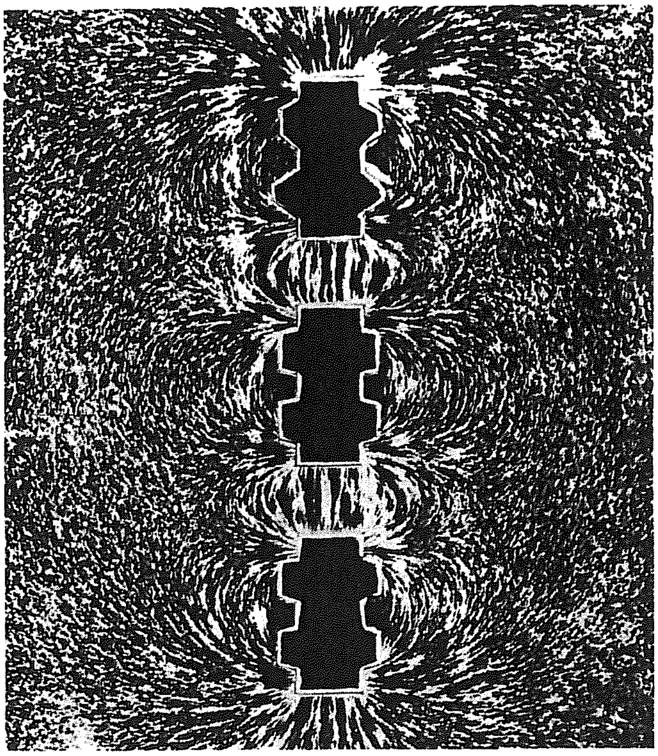

Fig. 4: Magnetic flux distribution for three reactor units

The layout of the whole insulation system was carefully investigated by means of electrolytic tank measurements as well as by calculations with the charge simulation method [6]. According to equal results the dimensions could be kept as small as possible. This is confirmed by Fig. 5, in which a photograph of the prototyp is shown. As for this prototype a plexiglass insulating cylinder was used, many details of the active part can easily be seen. All test results are summarized by the following nominal values:

V_n = 200 kV; I_n = 6 A (10 minutes); L_n = 51.5 H.

According to equs. (4) and (2) the SR-circuit with this single unit would be able to test a load of C_n = 46 nF with a frequency of f_n = 103 c/s. If four units are cascaded to achieve a voltage of 800 kV, f_n will remain the same if C_n is reduced to 46/4 = 11.5nF, a value which was quoted. The partial discharge inception voltage (sensitivity 5 pC) is higher than 220 kV, a voltage which was used as testing voltage for 45 minutes. The dimensions of the reactor are very small (diameter ≈ 500 mm; height ≈ 700 mm) as well as the weight of 0.25 kg/kVA for the nominal frequency, which would increase to 0.5 kg/kVA for a power frequency of 50 Hz. This number shows the real big improvement in comparison to HV-testing transformers or usual SR-circuits.

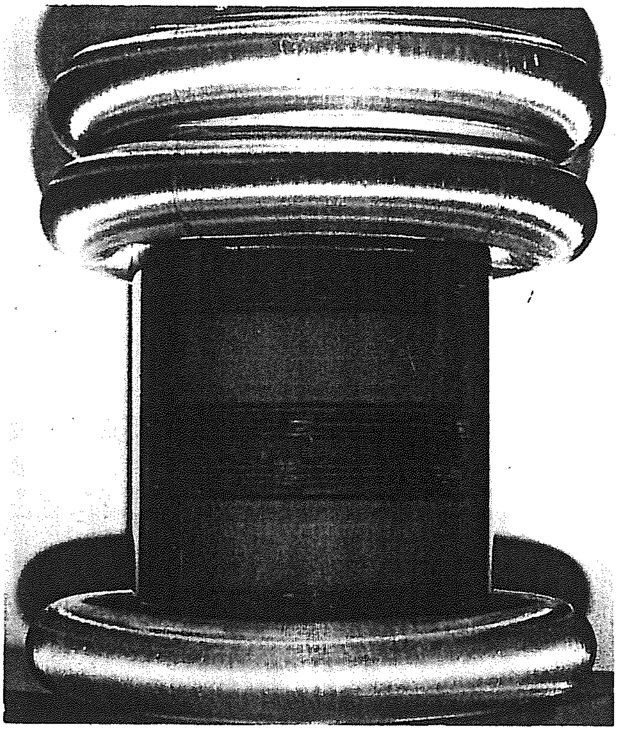

Fig. 5: The prototype reactor unit

The quality factor Q was tested in a wide frequency range up to about 100 c/s, which was possible as the natural resonance frequency of the reactor is 1800c/s. The dependency of Q from frequency f is shown in Fig. 6. For f $\gtrsim$ 50 Hz, Q is well above 50, which confirmes the excellent applicability for the reactor in a wide frequency range.

Finally it will only be mentioned that many flashover tests at full rated voltage and voltage distribution tests performed with a repetitive impulse generator have shown that no overvoltages within the windings exist.

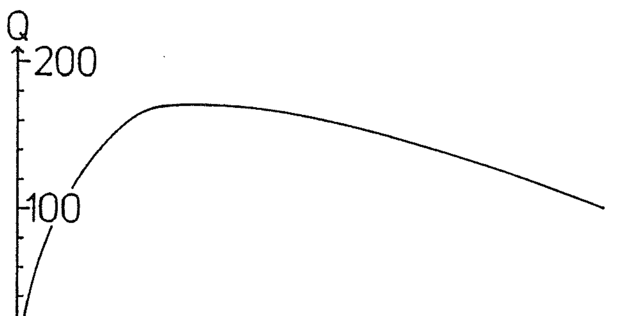

Fig. 6: Typical quality factor for the prototype reactor Fig. 5

B) Frequency converter

The frequency converter, connected to the mains supply, excites the SR-circuit with the resonance frequency and covers the losses of this circuit only, which are not higher than about 2 % of the reactive power. Such converters with thyristors are known i.e. for inductive heating of metals [5]. The special requirements for driving a HV-SR-circuit are concerned with the control of the high voltage and the interference elimination in order to get proper partial discharge measurements.

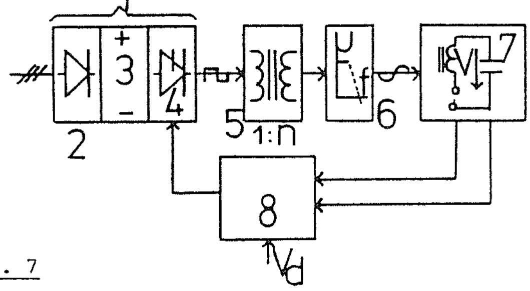

Fig. 7

Fig. 7 shows a block diagram of the converter with the control system. The circuit includes the frequency converter (1), which is based on a rectifier (2) and an inverted rectifier (4). In the intermediate circuit (3) there are HF-filters and capacitors for the compensation of the reactive power. The SR-circuit (7) is supplied via an exciter transformer (5) and a HF-filter (6).

The feedback circuit (8) contains two channels for the frequency and test voltage control. The converter represents, together with the SR-circuit and the feedback path for the frequency, an oscillator, which oscillates automatically on the resonant frequency of the series resonant circuit. The output voltage V was originally controlled by tiny deviations of the converter frequency from the resonant frequency. As, however, the sharpness of resonance of the HV-circuit is extremely high (Q up to 170), this method is inadequate. A good control is possible by the power factor cos ϕ, which is a measure for the active power injection into the SR-circuit. A pulse-width-control of the frequency converter is therefore best suited to achieve a continuous and stable control of the high voltage V. More details about the design of this converter will be published elsewhere.

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