Investigation of transformer insulation at high frequencies and high voltages

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Abstract: Derived by the increasing distributed electric power generation in correlation to large energy grids, there is a need for active compensation and power-flow control. Equally important is a linking of midsized offshore windfarms, on which a thyristor-based HVDC conversion and transmission would be inadequate, concerning money and space consumption. For the latter, IGBT-based valve technology is looking more promising. In relation to FACTS, the same could be used for STATCOM functionality, emitting both leading and lagging reactive power.

The use of that technology however, is posing non negligible problems with transformer insulation at the HVDC converter. The pulses used by the IGBT switches include much higher frequencies than the wanted 50/60Hz, due to their large slew-rate.

Therefore, material properties, e.g. electric strength, of common transformer insulation will be analyzed at frequencies of several 10kHz to some 100kHz. According to break down voltages of transformerboard around 100kV, at 50Hz and 1mm gap, HF-test-voltages of those amplitudes need to be generated. For that reason a source has to be designed and built, including a capacitor for the samples. With increasing voltage and frequency, corona effects are generating unwanted partial-discharge phenomena and need to be taken into account at the design.

INTRODUCTION

Still increasing demand for electric energy, combined with a broadly spread reluctance against nuclear power might lead into a gap in supply. Closing it with fossil fuels is surely not a liable option, since they are ebbing themselves and will be exhausted someday. Therefore alternative methods for energy production must be established as well as existing ones used and perfected. As an example of the latter, offshore windfarms can be noted as one plausible way, but requires significant changes to existing power grids.

Observed by the geographical situation in Germany, generation will take place in the most northern part of the country, while major consumption is located in the middle and far south. Therefore energy must be transported via that distance. Since the existing grid is not designed for such a long range transport, either new lines must be built, using HVDC technology, or extensive compensation and Power-Flow-Control must be implemented. Especially those Flexible AC Transmission Systems (FACTS) suitable for that task, such as United Power-Flow Controller (UPFC) and Static Synchronous Compensator (STATCOM) outline problems in implementation for their need of both leading and lagging reactive power. Therefore GTO or IGBT technology is necessary for the valves of the converters used in either one of the FACTS.

APPEARANCE OF HIGH FREQUENCY, HIGH VOLTAGE NOISE AT TRANSFORMERS

In HVDC transmission, Thyristors are usually implemented as valves in the converters. Conditional upon the current, the Voltage follows sinusoidal, given by the commonly known characteristics of a Thyristor. For high power links, that is the method of choice, but with certain limitations. Due to design, such a converter is only capable of providing lagging power and is therefore not usable for STATCOM functionality. Either GTO Thyristors or IGBTs must be used, as well as any other device with switch-off capability [1].

Especially Insulated-Gate-Bipolar-Transistors (IGBTs) are looking promising for utilization in that matter. In operation and design of such a converter, a fixed voltage of several kV is repeatedly switched on and off, resembling a kind of pulse-width-modulation, as shown in Fig. 1. with help of reactive elements, those pulses are equaled into the shown sine wave.

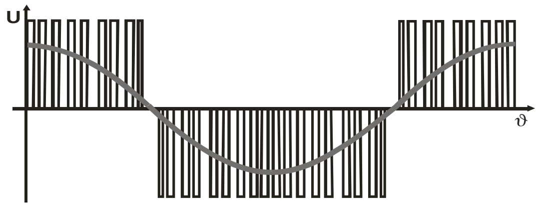

Fig. 1 Sine wave generation with IGBTs

Due to the large slew-rate of those pulses, as well as their repetition of some 10kHz, frequencies above the wanted 50/60Hz are generated by the converter. The subsequent filtering of the carrier component, generating the sine-wave, as well as the elimination of the high-level, high-frequency noise is the major challenge in the development of that technology.

Converter-valves with switch-off capability can not only be used for grid stabilization, as seen with the STATCOM. Similar converters are utilized in the UPFC, another FACTS element for Power-Flow-Control. Those can be used for better load-balancing throughout the grid and to use it to full capacity. Naturally high-level and high-frequency noise is generated here as well.

Apart from using fast switching elements in FACTS, those converters can also be used for feeding long distance separate networks. Especially having submerged cables, where direct current is the best choice. Thyristor valves can not be used in this operation, since they need a supporting net for commutation that is not present. IGBT converter stations could solve that problem, while having the big advantage of demanding minor required space.

Those designs have one, yet unmentioned element in common. For coupling of the grid and the converter, transformers are used. Due to the voltages and the converted power, those are manufactured using oil and cellulose insulation. Since this insulation system is usually stressed with low frequencies, material properties are only known at this range. Equally given is the dielectric strength for short pulses, such as lightning impulse voltages. Materials and completed transformers are well tested for those incidents and properties are taken into account in calculation and design. With respect to high frequency stresses by the IGBT valves, a save operating design can hardly be produced, for the lack of material properties. Hence, temporary use of fast switching technology, e.g. in motor-drives, requires a large amount of filtering and therefore further losses.

PROBLEM OF HIGH FREQUENCY, HIGH VOLTAGE SIGNAL GENERATION

Central to the investigation of high-frequency and high-voltage (HF-HV) material properties is the generation of those signals. A simple consideration reveals, that with both increasing frequency and level, the energy density of the signal is quickly rising too. Different approaches can be taken to generate such a signal and handle the power needed for the task. Basically one can think of generating a low voltage HF-signal that is transformed to the HV signal. That concept would require a ferrite core inside, since a iron core can not handle the desired frequencies. This fact is making the implementation virtually impossible, for ferrite being not the cheapest material to use in large quantities.

Used during investigations of polymeric insulations and enameled wires for converter powered machines were resonance transformer principles [2, 3], based on the Tesla-Transformer principle. They are triggered by a switching device, either a spark gap or MOSFET. The thereby excited primary resonant circuit is air-coupled to a secondary resonant circuit with the specimen. Both need to be operated at the same resonance frequency. Needless to say, that it is a challenge of adjusting them both.

More easy to handle is a marginal changed design, suggested by L. Rhode [4] and later likewise in [5]. Switching and control is done by vacuum tubes, generating a HF-signal of up to 100kV feeding the parallel circuit. According to

$$f_{res} = \frac{1}{2p\sqrt{L \cdot C}} \qquad (1)$$

the switching signal is adjusted and full oscillation is the result with the Reactor *L* and Capacitor *C*. This generator principle has however some disadvantages. A signal at high level needs to be switched. Additionally vacuum tubes are inconvinient in handling and operation. Elements of power electronics, such as MOSFETs and IGBTs are there a better choice.

RESONANCE CIRCUIT WITH FREQUENCY-VARIABLE INVERTER

With respect to the properties of MOSFETs or IGBTs the design needs to be changed. As shown in Fig. 2 a series resonance circuit is used.

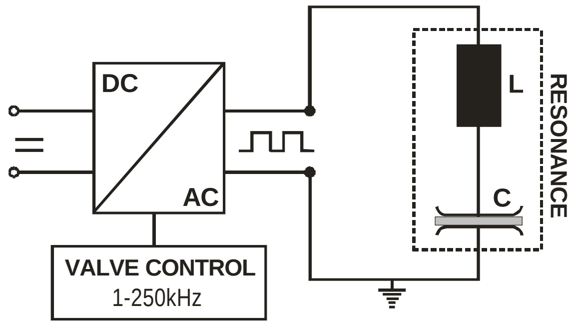

Fig. 2 Resonance circuit

Between the grounded side of the capacitor and the reactor it is excited with a low-level signal at resonance frequency according to (1). With the Inverter, a current is driven in the circuit that results in a voltage drop at the reactor.

$$U_{high} = wL \cdot I \qquad (2)$$

The desired test voltage U_{high} is generated thereby between L and C in Fig. 2.

The influence of the HF-HV signal is, even in this design, a limiting factor as well as the resistance of the used components. With respect to the Signal, the reactor is built with an air-core. Different materials, like iron, would not work or produce further losses in the circuit. Sharp edges and spikes need to be avoided in the design. Already at levels of 15 to 20kV, massive corona discharges would occur at those points. In a worst case scenario they trigger a failure of the reactor insulation. Then a fully loaded capacitor and with it all the energy stored in the resonating components, being now out of balance, will feedback into the inverter and might lead to its destruction. Apart from a scenario like that, prevention of further losses has yet another necessity. All the losses inside the resonator need to be directly fed by the inverter. Due to the frequency, up to wanted several 100kHz, the transmittable power is reduced significantly with the use of power electronics as valves. Hence, the circuit resistance needs to be minimized before, as well as kept there during operation.

The specimen that is investigated shall be placed in a capacitor with a plate-plate design to get a homogeneous field. With that assembly, a fixed value is achieved. Since the resonance circuit would be fixed to one frequency, either a tunable reactor or additional parallel capacitors need to be installed. Considerations on that matter are done with Fig. 3.

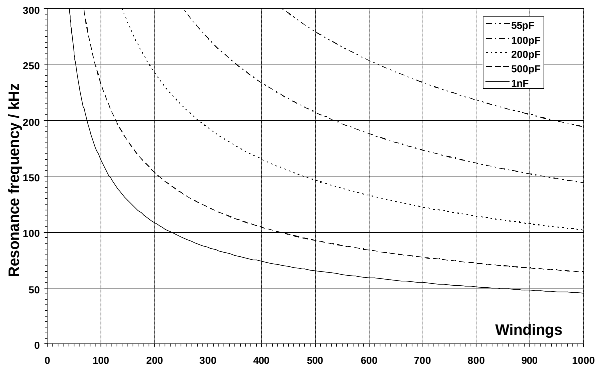

Fig. 3 Calculation of f_{res}

A calculation of the resonance frequency f_{res} over the number of windings *N* and therefore the length, with the capacitance as a factor, shows two basic design guidelines; the inductivity needed in (1) is calculated with the geometry of the reactor (length *l*, diameter *d*) by

$$L = p^2 \cdot \frac{N^2 \cdot d^2}{l} \cdot 10^{-7} \cdot \tfrac{H}{m} . \qquad (3)$$

For a rough tuning of the circuit a fixed reactor is chosen. Fine tuning is then done with a variable capacitor. Fig. 3 displays, that with short reactors, rather large resonance frequencies are accomplished, but a large capacitor is needed for reaching a low f_{res}. Since C_{min}, the minimal capacitance reachable, is limited by the specimen and its containment, longer reactors are better suitable for lower frequencies. Therefore a desired range selection is done with more or less windings. Fine tuning to an exact frequency is then accomplished with tunable capacitors that are additionally inserted in parallel to the specimen.

The remaining design considerations need to be done with the measurement of the signal at the probe. Most capacitor voltage divider are dampened with resistors. Hence they produce losses and should not be used. Despite of that fact they are, same as the transformer insulation, untested for the signals used.

CONCLUSION AND OUTLOOK

With the design specifications discussed in this article, a reliable apparatus for short and long term testing should be built. Preliminary data, gathered with a yet unstable operating test apparatus show a significant drop in material strength of transformer-oil at frequencies around 80kHz. For gathering more and reliable information, the design of the circuit elements needs to be refined and secured for safe operation. Shielding is a big issue there, since a non negligible part of the energy is radiated on non open frequencies, posing a problem e.g. with time-base signals (Germany: 77,5kHz).

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