Simulation Based Design of HF-Resonators for Damping of Very Fast Transients in GIS

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***Abstract*— Dielectric design of gas insulated switchgears (GIS) for modern AC ultra-high voltage power transmission lines is significantly influenced by undesired very fast electromagnetic transients (VFT) initiated by disconnector switching operations. This paper presents in detail a novel method for damping of VFTs by means of high frequency resonators and a numerical method for the resonator's eigenvalue analysis. The efficiency and accuracy of this simulation method for extraction of the resonant frequencies is validated by low-voltage AC measurements. The VFT damping efficiency of the developed resonator is verified by high-voltage VFT measurements.**

***Index Terms* — Very fast electromagnetic transients, electromagnetic modeling, numerical simulation, and cavity resonators.**

I. Introduction

The recent pronounced global tendency for reducing power transmission losses driven by dramatically increasing power demand resulted in development of new ultra-high voltage (UHV) AC power transmission systems, such as for example the new 1'100kV Jindognan – Nanyang - Jingmen line in China. Core components of the UHV AC systems are GIS that consist of HV switching devices (circuit breakers, disconnectors, earthing switches), various connecting pieces, and interface components (bushings) to overhead lines, transformers, etc. The GIS are installed in the nodes of HV networks to perform switching operations necessary for power system control and maintenance [1], [2].

As explained in detail in [1] and [2] the VFTs in GIS are initiated mainly by disconnector switching operation, they propagate as non-harmonic electromagnetic waves in the encapsulated GIS SF_6 volume, and they cause a very complicated transient voltage distribution with the peak values reaching theoretically 2.4 times a higher value than the nominal voltage [1]. As elaborated in [2], in the case of the UHV GIS the VFT overvoltages surpass the standardized lightning impulse withstand voltage level (LIWV) [3] and thus became the decisive factor for the dielectric design. This means that the size of the pressurized volume, i.e. the size of the complete UHV GIS installations is basically determined by the peak values of the VFTs and their efficient damping could lead to significant size decrease and radical cost reductions of the adjacent equipment (transformers).

The idea of damping the VFTs by means of HF cavity resonators, the initial resonator topology, and its first experimental verification was reported in a previous publication [4]. In the same work was also presented a numerical eigenvalue analysis of the resonator based on the time-domain vector Finite Element Method (FEM) [5]. The damping efficiency of the resonator was verified by measurements and the VFTs amplitude reduction of 20-30% was observed and reported [4].

In this paper the authors present the following: (a) a new and simpler eigenvalue analysis of the resonator based on the frequency-domain vector FEM [5]; (b) the results verification of the numerical eigenvalue analysis by low-voltage resonance measurements; (c) the VFT damping efficiency verification of the resonator by high voltage VFT measurements.

II. Method Description and Numerical Results

The topology of the cavity resonator according to our previous publication [4] is presented in Figure 1. The resonator consists of an elongated cavity with a narrow opening at its left end. As shown later in the paper, the cavity defines the inductance of the resonator and the gap its capacitance. The inductance and capacitance of the resonator determine its resonant frequency. Thus it is possible, by changing the resonator gap length and thickness and by changing the volume of the resonator cavity, to adjust its resonance frequency to the main component of the GIS VFTs. Precisely this was done in this work.

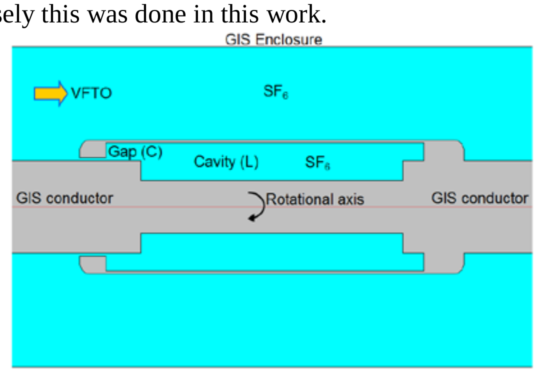

Fig. 1. The topology of the cavity resonator for damping of VFTs in GIS is depicted [4].

Theoretically speaking, Maxwell equations could be discretized in the resonator and surrounding GIS volume without any field sources by using the vector FEM. From the obtained homogenous linear system of equations we could extract theoretically the eigenvalues, i.e. the resonant frequencies and thus solve the problem [5]. However, in this case this is not possible for the following reasons: (a) the resonator is open and the corresponding leakage power makes the eigenvalues to be complex numbers; (b) it is not possible to calculate all the eigenvalues of the large FEM equation system but only a few eigenvalues around a certain predefined value that is in this case not known; (c) without a good initial guess the eigenvalue search would take inacceptable long CPU-time. These numerical effects has been already theoretically investigated and reported in detail in [6].

Therefore we suggest here a much simpler procedure. The model shown in Figure 1 at the left hand side is connected to a harmonic voltage source and on the right hand side terminated with the matching wave impedance in order to avoid reflections at the right termination boundary. At any given frequency the following boundary value problem (BVP) is solved by means of the vector FEM implemented in the software Comsol [7]:

$$\nabla \times \left(\nabla \times \vec{E}\right) - \omega^2 \mu\varepsilon \cdot \vec{E} = 0, (x, y, z) \in \Omega \quad (1)$$

$$\vec{n} \times \vec{E} = 0, (x, y, z) \in \partial_{PEC}\Omega \quad (2)$$

$$\vec{n} \times \left(\frac{1}{\mu}\nabla \times \vec{E}\right) + \frac{j\omega}{Z_s} \cdot \vec{n} \times \left(\vec{n} \times \vec{E}\right) = \frac{2j\omega}{Z_s} \cdot \vec{n} \times \left(\vec{n} \times \overrightarrow{E_s}\right) \quad (3)$$

$$\vec{n} \times \left(\frac{1}{\mu}\nabla \times \vec{E}\right) + \frac{j\omega}{Z_s} \cdot \vec{n} \times \left(\vec{n} \times \vec{E}\right) = 0, (x, y, z) \in \partial_{PORT}\Omega \quad (4)$$

where $\vec{E}$ is the electric field, ω is the angular source frequency, Ω is the pressurized SF_6 volume in and around the resonator, $\partial_{PEC}\Omega$ is the perfect electric conductor (PEC) boundary (all the metallic surfaces in the model), $\partial_{PORT}\Omega$ are the termination surfaces of the model with the known wave impedance $Z_S = \sqrt{\mu/\varepsilon}$.

Equation (3) defines the port, i.e. the surface over which the electric field of the source is known. This is the vertical model termination boundary on the left hand side of the model shown in Figure 1. Equation (4) defines the port with no source which is the boundary condition assigned to the vertical termination boundary on the right hand side of the model.

The BVP (1-4) is not a classical eigenvalue problem as it contains a field source ($\overrightarrow{E_s}$ in Equation (3)). However it is still the core of the eigenvalue extraction method suggested in this paper that consists of the following steps: (a) definition of the frequency range of our interest; (b) definition of the desired accuracy of the extracted eigenvalues, i.e. definition of the frequency step; (c) solution of the BVP (1-4) for each frequency step of the chosen range; (d) evaluation of the voltage across the resonator gap; (e) detection of the resonant frequencies from the peaks of the voltage curve.

This procedure was applied to two different resonators with the same topology shown in Figure 1 but with different cavity volumes. The obtained results are depicted in Figure 2.

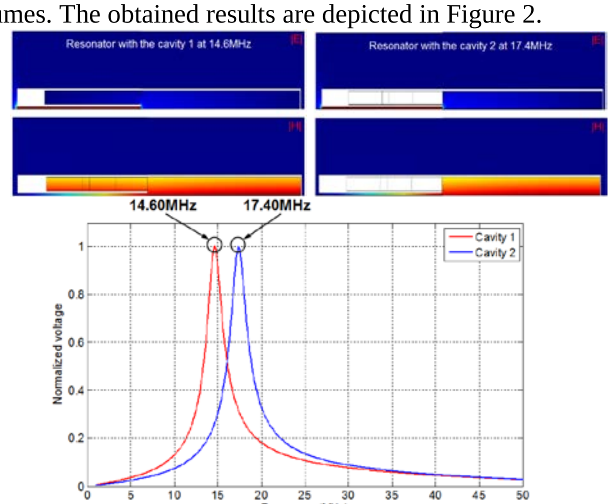

Fig. 2. The results of the resonator's eigenvalue analysis by solving the BVP (1-4) in the form of the eigenfields (top) and the voltage across the resonator gap (bottom) are shown.

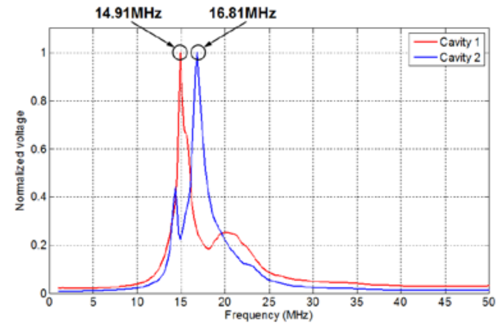

Fig. 3. The results of the LV resonance measurements of the fabricated resonators by using the network analyzer Agilent E5061B are presented.

In order to validate the simulation results the resonator with an adjustable cavity size was fabricated and its resonance curves were measured. These results are shown in Figure 3. It is evident from the comparison of Figures 2 and 3 that our method for eigenvalue analysis has a high level of accuracy as the disagreement of the measured and simulated resonant frequencies is less than 5%.

The VFT damping efficiency of the resonator with the resonant frequency of 14.91MHz (the cavity 1) was also tested on the ABB 550kV GIS installation type ELK-3. These results are shown in Figure 4. The damping effect of the resonator is evident as the dominant VFT component with the frequency of around 15MHz is reduced by almost 60%.

We are currently working on the full-Maxwell simulation of the entire installation ELK-3. These results together with the details of the resonator design will be presented at the conference and reported in the subsequent full paper.

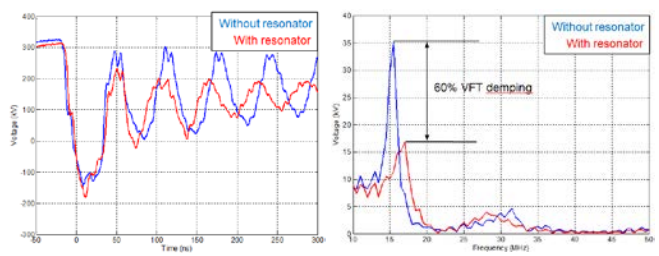

Fig. 4. The results of the VFT measurements on the ABB 550kV GIS installation type ELK-3 in time- (left) and frequency-domain (right) without and with the resonator are presented.

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