High Frequency Model of Magnetic Rings for Simulation of VFTO Damping in Gas-Insulated Switchgear with Full-scale Validation

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Abstract— Nanocrystalline magnetic rings have been experimentally proven for effective damping of Very Fast Transient Overvoltages (VFTO) in Gas-Insulated Switchgear (GIS). Application of any damping solution in specific GIS set-up (rated voltage, GIS arrangement) requires simulation-based design, which in turn requires reliable models with proven accuracy in demanding high frequency and high current VFTO conditions. This paper presents a new model of a magnetic ring, employing full frequency-dependent characteristics of the ring’s complex impedance, as well as the dedicated approach on modeling of the saturation effect of the material magnetization characteristics. The saturation effect is modeled by a bypassing branch, activated at certain saturation current value calculated according to the specific magnetic material properties and for the VFTO main frequency component. The model was implemented in EMTP-ATP simulation software and validated experimentally in a full scale 550 kV GIS test set-up. The validation proved applicability of the model for the assessment of VFTO damping effectiveness with the use of nanocrystalline magnetic rings, and thus for design of particular magnetic based damping solution in a specific GIS setting.

Index Terms— Very Fast Transient Overvoltages (VFTO), Gas-Insulated Switchgear (GIS), disconnector switch, magnetic ring, attenuation, damping, transients, switching

I. INTRODUCTION

A. Very Fast Transient Overvoltages in GIS

Very Fast Transient Overvoltages (VFTO) in Gas-Insulated Switchgear (GIS) originate from flashovers in SF6 gas, which occur mainly in the form of pre- and restrikes during switching operations of the GIS disconnectors. Due to the relatively fast breakdown in SF6, the transients are characterized by high voltage and high frequency, which may have a decisive impact on the dielectric design of the GIS components as well as jeopardize the insulation systems of the adjacent power equipment. Pioneering works on VFTO in GIS are dated back to 1982 [1]-[3]. Substantial effort invested so far towards mitigation of VFTO is constantly driven by the increase of the power system rated voltage levels, for which the insulation margins in regard of VFTO are being significantly decreased (e.g. IEC Std. [4]). These aspects became specifically of importance with the advent of Ultra-High Voltage (UHV) AC transmission in China and India, and with the pioneering works on UHV GIS developments, e.g. in [5].

Variety of existing VFTO mitigation methods have been recently reviewed in [6], [7]. The well-proven methods include disconnector equipped with a damping resistor [8], busbar with magnetic rings of different types (ferrite [9]-[11], amorphous [12], and nanocrystalline [11], [13]), and disconnector with reduced trapped charge voltage [14], [15]. In addition to the well-established methods, the new methods on VFTO damping are constantly emerging, giving an attempt to well understand and select the most appropriate solution (or a combination) for particular GIS application. The new methods include high frequency resonators [16], GIS busbar with inductive arrangement and surge arresters [13], and disconnector with modified contact system [17].

B. Damping of VFTO with Magnetic Rings

Application of magnetic rings is now proven experimentally, in the scaled down GIS [18]-[19] as well as in the full scale experimental set-up (since recently up to 550 kV) [11]-[13]. The method involves commercially available magnetic rings (of different types, sizes, and material properties), placed directly on the GIS conductor, and located under the electric field control screening elements eliminating large field gradients. In [12]-[13] the experimental results are supported with theoretical discussion on the dominant physical mechanisms which are seen as responsible for the VFTO damping effect in the magnetic material. These mechanisms include eddy current (and thus ohmic) losses, magnetic hysteresis losses, and saturation effect of the material magnetization characteristics. In [12], [19] the Authors compare experimentally the magnetic rings of ferrite and amorphous tapes, showing that the VFTO attenuation factor is significantly reduced by the saturation effect, and concluding that the suppressing effect becomes more evident when the cluster of the rings is long enough. In [12] the

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Authors compare different types and different number of nanocrystalline rings, concluding that the damping effect depends on the rings material properties (such as magnetic permeability) and dimensions, and increases approximately linearly with the number of rings involved.

Simulation-wise, the simplified approach is used for the time domain modeling of the magnetic rings in GIS, where constant inductance and resistance are involved (e.g. in [9]). This simplified approach does not include frequency dependence of the magnetic material parameters, neither its saturation in the high current conditions. In [20] a linear method based on the material frequency-dependent magnetic permeability is proposed for calculation of VFTO attenuation. The method has been qualitatively applied in [20] to selected time-domain results from [9], yet without inclusion of the saturation effects. Experiments presented in [21] indicated that the saturation effect can substantially limit the ferrite rings performance due to the rings saturation in high current VFTO conditions. Also in [11] it has been concluded that for high rated voltages the VFTO current causes that the flux density saturates the magnetic material, leading to significant decrease in the attenuation effect. In [19] the saturation effect was included in the analytical formulas, indicating that it can be the major factor deciding of the VFTO damping overall efficiency.

In this paper, we present a new model of the magnetic ring, which is intended for the time domain simulations of VFTO damping in GIS. Since the losses mechanisms in the magnetic material show both frequency dependence and saturation, and the overall VFTO damping effect is strongly influenced by the saturation effect, the presented model is both frequency dependent as well as it includes the magnetic saturation effect. The frequency characteristics of the model covers full frequency band-width of the VFTO occurring in a real GIS setting.

The simulation model proposed in this paper has been validated against experimental data measured in a full-scale 550 kV GIS set-up. The measurement set-up has been described in [13] as providing real high frequency and high current VFTO conditions. For the model validation we selected the nanocrystalline rings and data used in the experimental work [13]. The rings provide relatively high attenuation due to their good permeability characteristics and high saturation flux density.

The paper is organized as follows: Section I gives the motivation and background for the work presented in this paper. Section II introduces the new model of the magnetic rings, with description of the modelling of the full-scale 550 kV GIS test set-up of [13] used for the model validation here. Section III reports on the model validation with experimental results and Section IV gives exemplary simulation results with respect to number, types, and arrangements of the rings within the GIS busbar. Finally, conclusions are drawn in Section V.

II. HIGH FREQUENCY MODEL OF MAGNETIC RING WITH SATURATION EFFECT

A. Model Overview

For the VFTO conditions, current waveforms associated with the overvoltages propagating through the GIS bus-ducts are characterized with the peak values reaching kA and the frequencies up to 100 MHz (thus belonging to the transient phenomena in power system with the highest frequencies). For typical nanocrystalline rings, with the diameters fitting to the HV/UHV GIS conductors, and for the ring typical saturation magnetic flux density ($B_{sat} = 1.2$ T), the saturation current $i_{sat}$, is of order of several tens of amperes. When the current associated with the VFTO is propagating through the magnetic ring, its high amplitude and high frequency leads to rapid transition of the ring from its linear to the fully saturated state. With that assumption, the detailed shape of the saturation curve can be simplified and approximated with two linear sections, which defines two modes of the magnetic material operation: frequency dependent linear mode, and saturated mode. The model is then switched between these two working regimes, according to the instantaneous current value $i$ flowing through the GIS busbar, and its relation to the saturation current $i_{sat}$.

Fig. 1 shows an illustrative example of the model implemented in EMTP-ATP simulation software, where the two parts of the model are indicated, representing the two working regimes: linear frequency dependent (in blue color), and saturated (in red color). The linear part represents the critical region in B(H) characteristics of the ring (see Fig. 1, left), and includes frequency dependent inductive behavior as well as the total magnetic losses. This part is modeled as a lumped element equivalent circuit composed of a set of $RL$ elements (see Fig. 1, right). The saturation effect is included by bypassing the linear part for the current values $i$ exceeding the saturation level $i_{sat}$.

This approach includes both frequency characteristics and saturation effect of the magnetic material, as required for VFTO conditions. Fig. 1 depicts exemplary implementation of the bypassing branch in EMTP-ATP software, modeled by the current-controlled resistor connected in parallel to the $RL$ branch.

B. Linear Part: Model of Frequency Dependent Impedance

The linear part of the model represents the frequency dependent complex impedance characteristics of the ring $Z'(f)$, measured at low current conditions, in the frequency range covering full band-width of the VFTO. The complex impedance, measured at any given frequency $f = \omega/2\pi$, represents both the inductive behavior as well as the total losses...
displaced in the magnetic ring:

\[ Z^* \sim j \omega \mu_0 (\mu' - j \mu'') \]

where real \( \mu' \) and imaginary \( \mu'' \) parts of the complex permeability. They account for the inductive behavior and for the total losses respectively.

The impedance is represented by a lumped element equivalent circuit consisting of \( k \) inductive \( L \) and resistive \( R \) elements (typically the number of elements involved: \( k = 7 \)). General aspects of the circuit synthesis basing on the impedance characteristics are presented e.g. in [22], while its application for nanocrystalline rings in the frequency range from 10 kHz to 100 MHz is presented in [23]. Based on the method presented in [23] we identified the lumped element equivalent circuits representing nanocrystalline rings of three types, as used in the full-scale 550 kV measurements in [13].

Frequency response of each equivalent circuit was validated by comparison of the simulated complex impedance characteristics with the measured one. Fig. 2 shows frequency characteristics of the complex impedance for an exemplary ring as used in this paper (the inset in Fig. 2 shows the lumped element equivalent circuit representing the approximated characteristics). The model covers the entire frequency range characterizing the VFTO conditions (from 10 kHz to 100 MHz).

**TABLE I**

<table>
<thead>
<tr>
<th>Ring</th>
<th>sat ( A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Type</td>
<td>60</td>
</tr>
<tr>
<td>B-Type</td>
<td>60</td>
</tr>
<tr>
<td>C-Type</td>
<td>160</td>
</tr>
</tbody>
</table>

It should be mentioned that the saturation current \( i_{sat} \) can be either calculated analytically or it can be the model parameter, being adjusted to achieve good agreement between the simulation and the measurement results for a given rings arrangement.

**Fig. 2.** Frequency characteristics of exemplary magnetic ring (A-Type): amplitude (phase) in blue (red) colors; dots: measured, lines: approximated; inset: lumped element equivalent circuit synthesized for approximated impedance; \( R_0, \ldots, R_7 \) = (1.5, 8.0, 5.7, 5.4, 6.2, 8.7, 15.8, 104.0) \( \Omega \), \( L_1, \ldots, L_7 \) = (22.4, 35.5, 1.2, 0.6, 0.3, 0.2, 0.1) \( \mu H \)

**Non-linear Part: Model of Saturation Effect**

The saturation effect limits the magnetic rings ability to suppress the VFTO: the magnetic flux density induced by the current associated with the VFTO (up to kA order) significantly exceeds the saturation value of the rings (of tens amps order for given types and dimensions). The non-linear part of the model representing the magnetic saturation of the ring is thus introduced to the model by an additional branch bypassing the linear part of the model (representing \( \mu_0 \) conditions) for the current instantaneous values exceeding the level of saturation: \( i \geq i_{sat} \).

The method of calculating the saturation current value \( i_{sat} \) for the magnetic rings of given type and dimensions was studied separately and described in detail in an accompanying paper in preparation [24]. The method allows for calculation of frequency dependent saturation current \( i_{sat} \) based on the ring complex impedance (measured), and typical material properties as provided by the rings manufacturers (such as saturation flux density, geometry, and ribbon thickness). While in general the saturation current \( i_{sat} \) is frequency dependent, in our model we use its constant value calculated for the main frequency component of VFTO. For the test set-up introduced in [13], which we use for validation of our model, the main frequency component of VFTO is 15 MHz. Table I shows the saturation current \( i_{sat} \) calculated for the frequency 15 MHz, for the three types of nanocrystalline rings we use in this paper for validation of our model according to the experimental results presented in [13].

Fig. 3 shows exemplary current waveforms in different parts of the magnetic ring model according to Fig. 1. The waveforms were obtained for the ring model applied to the model of the real GIS set-up, as introduced further in Section III.A (see Fig. 5). Fig. 3 illustrates that the current flowing through the linear part of the model is always lower than \( i_{sat} \).

**III. Model Validation**

The model proposed in this paper was validated with the measurement results presented in [13] for the full-scale experimental set-up of 550 kV GIS. The simulations were conducted for the nanocrystalline rings, of the same types and dimensions as used in [13] so that comparison between simulated and measured signals could be made.
A. Full-scale 550 kV GIS Test Set-up

Fig. 4 shows the measurement set-up described in [13] and its representation in EMTP-ATP simulation software, including the indication, where the rings (of different number and types) were inserted.

The measurement set-up (see Fig. 4, top) consists of the 550 kV GIS components with the sparking gap compartment filled with SF$_6$ gas. High voltage impulse is supplied via bushing from the 1.2/50 µs generator. Breakdown in the sparking gap occurs according to the gap distance and the SF$_6$ gas pressure. The VFTO is constituted by the multiple reflections from the GIS components, the bushing and the open end busbar. The main VFTO component (15 MHz) is associated with the overall length of the set-up. Capacitive sensors and digital oscilloscope are calibrated for the full VFTO bandwidth.

Simulation model of the GIS set-up (see Fig. 4, bottom) was built according to [26]. It includes surge impedances modeling the GIS busbars, lumped capacitances modeling the spacers and the elbows, voltage source modeling the impulse generator. The spark-gap (SF$_6$ breakdown) is modeled as a nonlinear resistance given by the exponentially decaying formula with the time constant specific to the SF$_6$ gas pressure.

![Rings model insertion](image)

The VFTO was generated by a discharge of 1.2/50 µs impulse voltage (supplied from the Marx generator) in a spark gap compartment (see Fig. 4). The VFTO characteristic parameters (amplitude and steepness) were reproduced by the GIS bus-bars arrangement. Throughout the paper we define the VFTO attenuation factor as:

$$\frac{u_{\text{ref}}^{\text{max}} - u_{\text{max}}^{\text{max}}}{u_{\text{max}}^{\text{ref}}} \times 100\%, \quad (1)$$

where $u_{\text{max}}^{\text{max}}$ means global VFTO maximum, for the waveform $u_{\text{ref}}^{\text{max}}$ obtained with the rings involved, and for the reference waveform $u_{\text{max}}^{\text{ref}}$ without the rings. As an example, the global maxima of the VFTO are marked in Fig. 5 and Fig. 6.

To validate the proposed model of the magnetic ring, we conducted simulations with the GIS (see Fig. 4, bottom) with the use of the magnetic ring model (see Fig. 1), and compared the results with the measurement results obtained in the 550 kV GIS test set-up [13] (see Fig. 4, top).

B. Model Validation for 8 Rings of A-type

Fig. 5 and Fig. 6 show the measurement and the simulation results respectively, for the case with 8 rings of A-type.

It should be noted, that the simulation model of the GIS set-up does not fully reproduce the reference case. Especially the rapid decline of the amplitude after the first peak in the measurements (Fig. 5, red line) is not present in the simulations (Fig. 6, blue line). However, the main features of the waveform were reproduced correctly and thus the simulation model of the setup should be appropriate for comparisons of the attenuation factors.

For $i_{\text{sat}} = 60$ A (as calculated according to [24], see Table I) the simulated global maximum attenuation was 6.5%, which was already in a good agreement with the measured value of 7.7%. In order to achieve a better match between the simulations and the measurements, the saturation current value was considered as the model parameter, and increased from 60 A to 90 A. It should be noted, that the order of magnitude of the matched value ($i_{\text{sat}} = 90$ A) is the same as of that calculated ($i_{\text{sat}} = 60$ A, see Table I). Fig. 6 shows the simulated waveforms for $i_{\text{sat}} = 90$ A.

It can be seen that the attenuation factor depends on the saturation current $i_{\text{sat}}$ assumed in the model. As expected, higher saturation current leads to higher attenuation factor (7.7% for 90 A as opposed to 6.5% for 60 A).

C. Model Validation for Different Number of Rings of C-type

Fig. 7 shows the measurement results for the case with different number of rings of C-type (according to Table I). Fig. 8 shows zoomed first peak of Fig. 7. The number of rings involved were 2, 5, 10 and 20. Fig. 9 shows the simulation results for the same ring type and the number of rings, presented in the same scale as the measurement results in Fig. 8.

The saturation current of $i_{\text{sat}} = 160$ A was assumed in the model, as calculated according to Table I. Good agreement for the global VFTO maximum attenuation (first peak) was achieved between the measured and simulated results (see Tables II and III respectively). In both cases, the attenuation increases with the number of rings involved. In [12] the increase of the VFTO damping effect with the length of the ring cluster

![Measurement results for case with 8 rings of A-type (blue), reference signal (no rings) is denoted in red color](image)

![Simulation results for case with 8 rings of A-type (blue), reference signal (no rings) is denoted in red color; saturation current: $i_{\text{sat}} = 90$ A](image)
is observed up to almost complete attenuation (as for the increasing number of rings in [13], [25]). In our simulations this linearity is well reproduced (see Table II and III).

Despite the good agreement between the simulation and the measurement results, it should be noted that the magnetic ring model we present relies on the measured frequency characteristics of the complex impedance, which may (and usually does) significantly differ between the rings of the same type.

IV. EXEMPLARY SIMULATIONS WITH THE NEW MODEL

In this section we present exemplary simulations which can serve as exemplary area of application of the proposed model.

A. Simulations for Different Types of Rings

Fig. 10 shows simulation results for the case with 8 rings of three different types (denoted as A-B-C, according to Table I). The saturation current $I_{\text{sat}}$ was assumed 90 A for the A-type ring, 60 A for the B-type ring, and 160 A for the C-type ring (for B-C types according to Table I, for A-type as per Section III.B).

Table IV gives attenuation factors read from Fig. 10. It can be seen that the attenuation is the highest for the A-type ring, intermediate for the B-type ring, and the lowest for the C-type ring. This ordering is as expected according to the permeability values of different ring types at MHz frequency range (see Table V). As shown in [12], the attenuation factor (above some length of the rings cluster) depends strongly on the relative permeability of the magnetic material used, even more dominantly than on the level of the saturation flux density $B_{\text{sat}}$. It is shown in [12], that the ferrite rings give higher attenuation than the amorphous rings despite that the amorphous rings pose almost three-times higher saturation flux density. At the same time however, they have lower values of the high frequency permeability, as compared to the ferrite rings.

In our case, the saturation flux density for all types of rings was the same, $B_{\text{sat}} = 1.2$ T, and the ordering of the attenuation factor (see Table IV) matches with the ordering of the high frequency permeability (see Table V for 1 MHz).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
No of rings & Global maximum [kV] & Attenuation [%] & attenuation per ring [%] \\
\hline
0 (Ref.) & 353.3 & - & - \\
2 & 347.6 & 1.6 & 0.81 \\
5 & 341.3 & 3.4 & 0.68 \\
10 & 338.7 & 4.1 & 0.41 \\
20 & 311.3 & 11.9 & 0.59 \\
\hline
\end{tabular}
\caption{Attenuation factors for different number of rings of C-type: simulation results}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
No of rings & Global maximum [kV] & Attenuation [%] & attenuation per ring [%] \\
\hline
0 (Ref.) & 353.3 & - & - \\
2 & 349.2 & 1.2 & 0.58 \\
\hline
\end{tabular}
\caption{Attenuation factors for different number of rings of C-type: simulation results}
\end{table}
The highest global maximum attenuation is for the arrangement (c). This can be explained by that the discontinuity of the surge impedance introduced by the rings can be decreased by the distances between the rings, which can influence the effective transmission and reflection coefficients from the rings, and thus influence: the VFTO propagation, shape of its waveform, and finally the attenuation factor. In our case, the arrangement which gives the highest attenuation is when the rings are evenly distributed along the GIS busbar – arrangement (c) in Fig. 12. This arrangement can be seen as also advantageous from mechanical and thermal design perspectives, however the need for more space in the GIS busbar is a clear disadvantage in this case.

V. CONCLUSIONS

Attenuation of VFTO in GIS using magnetic rings should include an optimum use of a magnetic material to provide the required damping effect with the minimized impact on other GIS design factors, such as the dielectric or thermal properties. Accurate models of the magnetic rings allows one to optimize the design using simulations and thus to reduce the experimental and the design costs of the damping solution.

The new model of the magnetic ring was introduced in this paper. The model covers two important features of the magnetic rings in this particular application: frequency dependence of the inductive and resistive behavior (including its total losses) of the ring, and saturation effect which causes that the ring become inactive when the material becomes saturated. These aspects are critical for modeling of the magnetic material in high frequency and high current VFTO conditions. In the model presented two simplifications were made: i) the frequency characteristics was assumed the same for all currents in the whole linear region, and ii) the saturation curve has been approximated by the two linear sections.

Despite the simplifications mentioned the model allows one to determine the length of the rings cluster (or the number of the rings employed) which is needed to achieve the required damping effect. It also allows one to select the type of the magnetic material and its geometry, providing the highest attenuation for a given number of rings employed (the model is based on the measured frequency characteristics of the ring of specific type and dimensions, as well as on its material properties). Further, the approach presented enables optimization of distribution of damping rings along the GIS busbar.

The approach presented in the article has been validated using experimental data obtained at a full-scale test set-up comprising a 550 kV GIS. This proves its applicability for the assessment of the VFTO damping effectiveness with the use of nanocrystalline magnetic rings.

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VII. REFERENCES

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