Hybrid Model for Air Core Reactors in EMC Simulations of High Voltage Converter Stations

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***Abstract*—Recently, accurate EMC simulation methodologies for high voltage converter stations have been developed and presented. These methodologies can model complete substations, and cover conducted and radiated emissions. The simulations rely on numerical full-wave methods coupled to circuit solvers. Main subject of this study are the air core reactors used in such high voltage converter stations. They have complex geometries and are therefore typically included in system models as impedance netlists only. As a consequence, electromagnetic coupling and radiation effects of the reactors are neglected, what can negatively impact the accuracy in cases where they are installed outdoors or near other components. In this paper, we present a hybrid approach for efficient modeling of air core reactors as part of large, system-level models of medium and high voltage converter stations. The model consists of a simplified 3D single-turn coil, coupled to a circuit model at schematic level. The correct magnitude of the magnetic field is obtained by multiplying the winding current by the number of reactor turns and injecting them into the 3D single-turn coil using an ideal transformer. Implementation is done in CST Microwave Studio. The results are compared to measurements, to equivalent lumped circuit models and to full wave simulations.**

Keywords—reactor; impedance; radiation; EMC; simulation; high voltage; medium voltage; converter; substation

I. INTRODUCTION

Today's medium and high voltage converter stations are based on fast switching power electronics for increased performance and efficiency. With this, the need for thorough analysis of the electromagnetic interferences (EMI) is increasing and numerical approaches for predicting electromagnetic compatibility (EMC) are being developed. A methodology for EMC simulations of complete substations, based on CST Microwave Studio was presented in [1] and [2]. The papers have demonstrated high prediction accuracy for conducted and radiated electromagnetic disturbances in the frequency range from 10 kHz — 10 MHz. A known limitation however, is that the converter reactors (Fig. 1) are modelled as impedance models only, without coupling or radiation properties. This limitation can be acceptable if the reactors are installed inside a shielded hall. In many cases however, the reactors are installed outdoors, where electromagnetic coupling and radiation cannot be neglected anymore. This work is therefore presenting an approach to efficiently include air core reactor coupling and radiation into large, system-level EMC models for the target frequency range of 10 kHz — 10 MHz.

Air core reactors are key components in most medium and high voltage substations (Fig. 1). They are used as smoothing or filtering inductors in high voltage direct current converters, as controlled inductances in static var compensators or as phase reactors in multi-level converter applications [3]. As phase reactors and smoothing reactors, they are dimensioned to carry the full substation currents, which can be up to several kilo-amperes. Because of these high current ratings and inductance values of up to 50 mH or more, the reactors can get several meters in height and diameter and are mounted several meters above ground for electrical insulation purposes.

The windings have up to 10 to 100 turns and are typically constructed as parallel connected, concentric layers, separated by cooling ducts (Fig. 2) [3]. Modeling such a geometry in a 3D numerical environment requires large and fine meshing [4]. Including multiple such reactors in a converter system model as presented in [1], would therefore be numerically very inefficient. The model presented in this paper is exploiting the fact that the reactors have typically simple impedance characteristics within the frequency range of interest (Fig. 3). This allows to add coupling and radiation effects without significantly increasing the total computation effort.

Fig. 1 Photograph of actual air core reactor.

II. AIR CORE REACTOR

The reactor investigated in this work has a nominal inductance of $L = 1$ mH and physical dimensions as shown in Fig. 2. The winding is rated for a nominal current of $I = 2.5$ kA and is constructed in four parallel layers with an average of $N = 38$ turns per layer. Fig. 3 shows the measured impedance for the frequency range of 40 Hz — 10 MHz. The impedance was measured using an Agilent 4294A precision impedance analyzer. The curves clearly show two resonances. The first resonance at $f_1 = 325$ kHz is the parallel LC resonance formed by the coil inductance $L = 0.98$ mH and the total turn-to-turn capacitance $C_{par} = 240$ pF. The second resonance at $f_2 = 4.34$ MHz is a series LC resonance formed by the series connection of the capacitance C_{par} and the measurement wiring inductance L_w. The reactor terminals are at opposite ends of the cylinder; hence the measurement wires had to be placed far from each other, resulting in a large but well-defined inductance and a negligible parallel capacitance. The inter-layer capacitance can also be neglected as the four layers are connected in parallel.

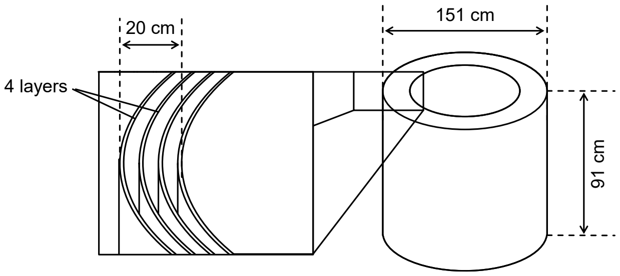

Fig. 2 Dimensions of air core reactor investigated.

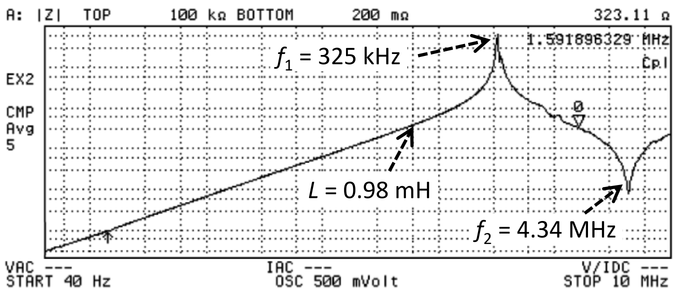

Fig. 3 Measured impedances of the air core reactor.

The magnetic fields corresponding to the inductive winding currents I_L and the displacement currents I_C through the turn-to-turn capacitances C_{par} are shown in Fig. 4. As shown in [3], for high current air core reactors, as addressed in this work, this fully characterizes the magnetic fields within our frequency range of interest (10 kHz — 10 MHz).

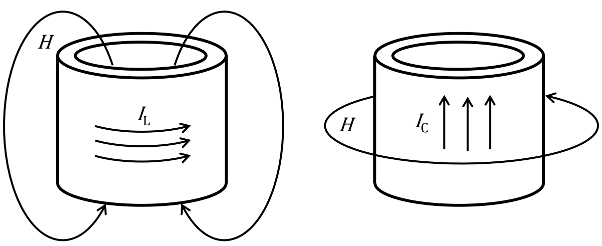

Fig. 4 Magnetic fields H related to inductive winding currents I_L (left) and capacitive displacement currents I_C (right).

III. PROPOSED HYBRID MODEL

The reactor models for the system-level CST EMC simulations must include the characteristics discussed in the previous section: impedance with LC resonances, H-field characteristics for the winding and displacement currents, and capacitive coupling to other components and to ground. For this, we choose a hybrid approach, consisting of a 3D coil model coupled to a circuit model, and which can be implemented in CST Microwave Studio (Fig. 5).

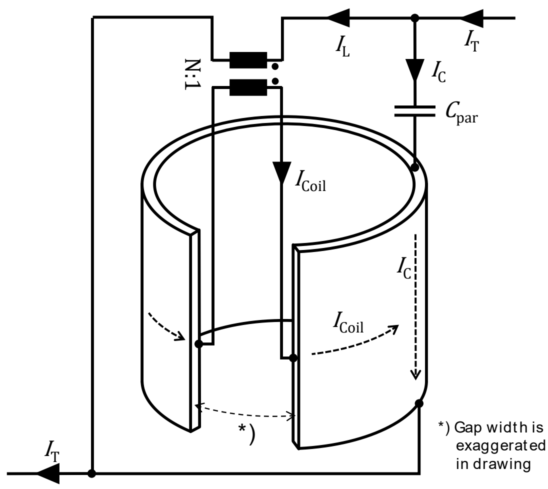

Fig. 5 Schematic representation of the hybrid model.

The principle of the hybrid approach is to model a single-turn cylinder with the outer dimensions of the actual reactor and to horizontally inject the winding currents I_L multiplied by the turns number N using an ideal transformer. The resulting injected current I_{coil} represents the total coil current that generates the magnetic field. In parallel, the displacement current I_C is vertically injected into the 3D structure via the equivalent turn-to-turn capacitance C_{par} (Fig. 5). The inductance L_N seen at the reactor terminal therefore corresponds to the single turn inductance L_S of the cylinder structure multiplied with N^2 (Fig. 6).

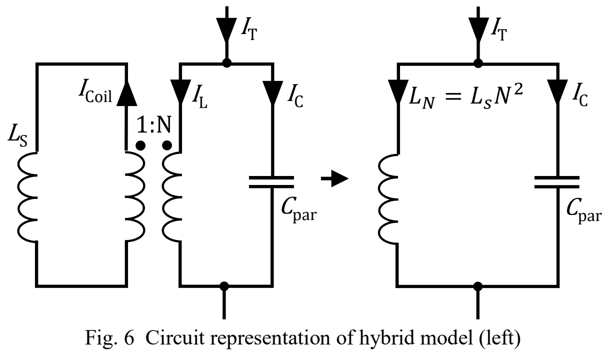

Fig. 6 Circuit representation of hybrid model (left) with resulting equivalent LC circuit (right).

The currents I_{coil} and I_C through the 3D model of the single-turn cylinder are forming the magnetic fields as illustrated in Fig. 4. Additionally, the 3D structure also inherently includes the reactor's stray capacitance to ground and all coupling effects to the surrounding 3D substation model components.

IV. Model Verification

Fig. 7 shows the CST 3D model of the reactor introduced in Fig. 1. It includes the single turn cylinder, the wiring and the three ports for winding current injection (port 1), the displacement current injection (port 2) and the bypass path for the ideal transformer (port 3). The corresponding circuit model in CST is shown in Fig. 8. The circuit includes the ideal transformer with the 38:1 ratio, the parallel capacitance C_{par} = 240 pF, the 1 V impulse source and an additional small resistor for stable convergence of the time domain TLM solver.

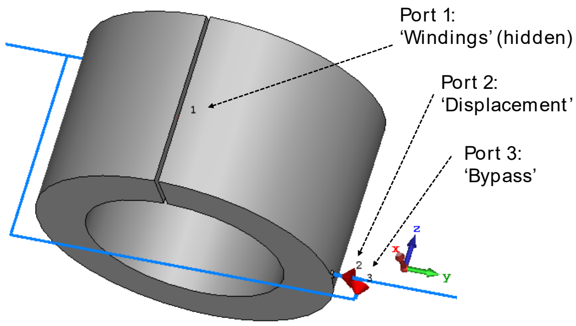

Fig. 7 3D CST implementation of hybrid model showing the single turn cylinder, the wires and the three port connections.

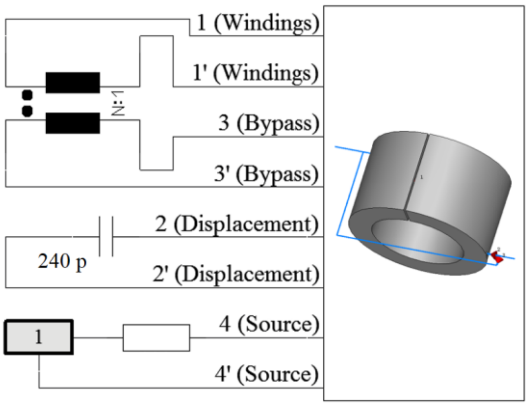

Fig. 8 CST schematics of hybrid model with the ideal transformer.

For verification, we first compare the hybrid model with a *lumped* model, a variant where the cylinder port 1 is shorted and the ideal transformer replaced by the actual L = 1 mH reactor inductance (Fig. 9). The objective of the lumped model is to provide a reference simulation with the correct inductance. In contrast, the lumped model will not create the correct magnetic field since the current is flowing mainly vertically through the cylinder and without multiplication with the turns number. The 3D structure will however include stray capacitances to ground and the series inductance L_w of the connection wires. Therefore, we can expect the same impedance with the two resonances at f_1 = 325 kHz and f_2 = 4.34 MHz, respectively.

The simulation results in Fig. 10 and Fig. 11 show the port currents in the reactor for the *hybrid* model and the *lumped* model, respectively. Since the models where excited with a constant 1 Volt source, the currents correspond to $1/|Z|$. As expected, the winding currents (dash-dotted line) in the hybrid model is 38 times the bypass current (dotted line) through the ideal transformer (Fig. 10).

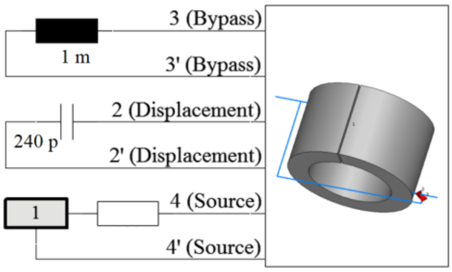

Fig. 9 CST schematic of reference model with lumped inductance.

The comparison between the hybrid model (Fig. 10), the lumped model (Fig. 11) and the measured reactor (Fig. 3) shows good agreement for the reactor inductance and for the first resonance frequency. The second resonance is slightly higher for the simulations (f_2 = 5.3 MHz) compared to the measurement (f_2 = 4.34 MHz). This is caused by the different connection wire layout used, resulting in different series inductance L_w.

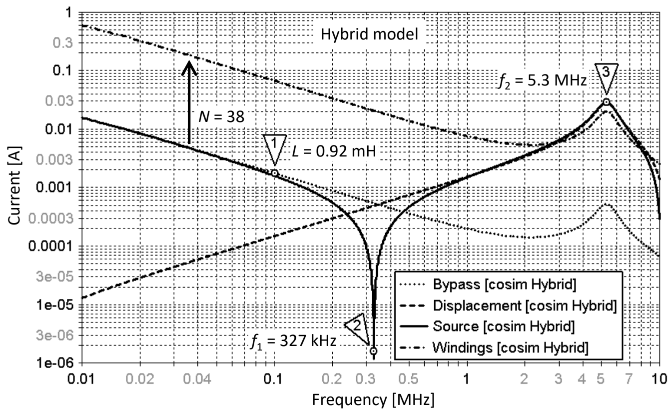

Fig. 10 Simulated currents in *hybrid* model, for a source excitation of 1 V.

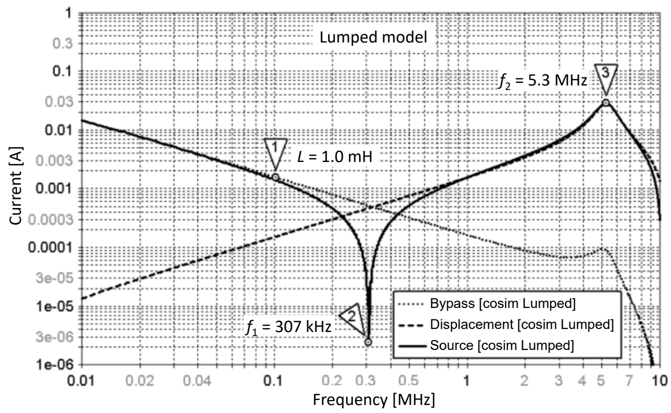

Fig. 11 Simulated currents in *lumped* model, for a source excitation of 1 V.

Fig. 12 plots the magnetic field vectors at f = 300 kHz, inside and outside the reactor. The fields at this frequency are formed by the inductive coil current I_{coil} and correspond to the expected, pattern as shown in Fig. 4 (left) and discussed in [3]. It also shows that at the frequency f_1 of the LC resonance, the magnetic field from the inductive winding currents still dominates over the field from the capacitive displacement currents. The reason is that at the resonance frequency, the total coil current I_{coil} is still $N = 38$ times higher than the displacement current I_C (Fig. 10). Finally, a quantitative comparison is done using a slightly less complex reactor with only 10 turns on 3 layers. It is simulated with the hybrid model and a full model that resolves all individual winding turns. Fig. 13 compares the field strengths at various distances and Fig. 14 compares the field vectors in proximity of the windings. Both plots show very good agreement.

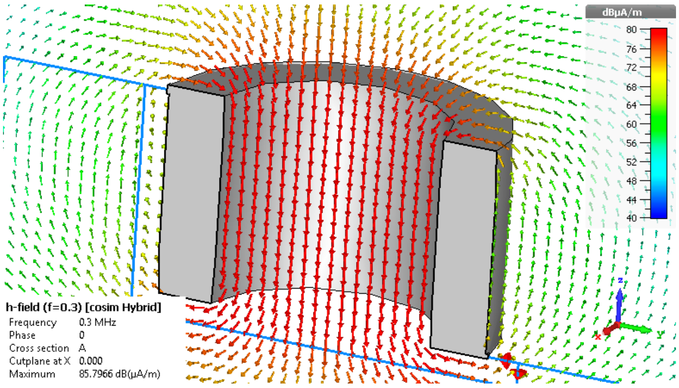

Fig. 12 H-field at 300 kHz, formed by the coil current I_{coil}.

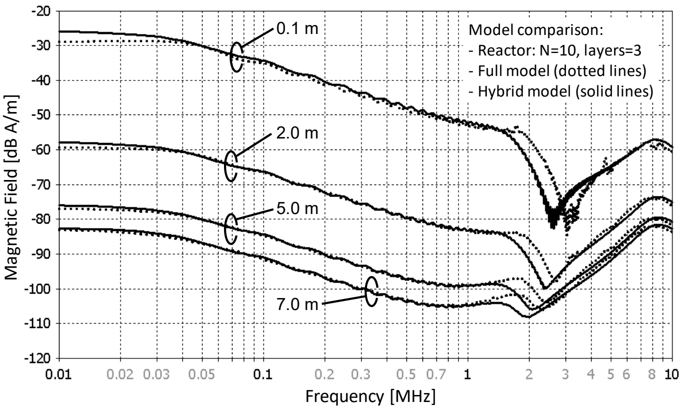

Fig. 13 H-field strengths at 0.1, 2, 5 and 7 m distance from the reactor.

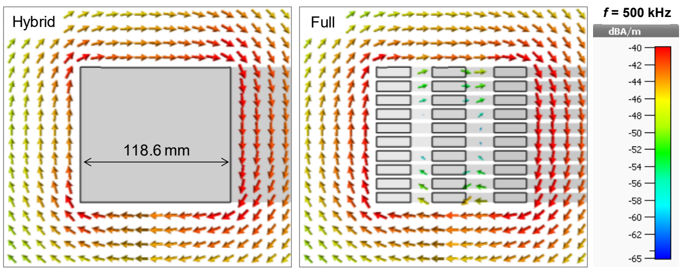

Fig. 14 H-field vectors around hybrid (left) and full (right) reactor windings.

V. Conclusion

In this work, we have used a hybrid approach to efficiently model large air core reactors typically comprising tens of turns in each of multiple, parallel-connected winding layers. The benefit of the hybrid model described is that, unlike the simplest, lumped LC model, it provides not only accurate impedance, but it also covers radiated fields within our frequency range of interest (10 kHz — 10 MHz). The models have been implemented in CST Microwave Studio as part of an EMC simulation methodology for medium and high voltage converter substations [1], used for prediction of EMC disturbances.

The efficiency of the hybrid model allows to include multiple reactors in system-level EMC models of complete substations. Depending on the overall station complexity and the number of reactors, the computation time increases only by about 10..20%, compared to the previous cases where reactors were modelled as impedance netlists only.

With the new reactor models, the accuracy of EMC noise level prediction is further improved. Besides that, the new models also enable a whole range of electromagnetic studies not possible with the simple LC representation of reactors. Those are: determination of the ideal placement of reactors in the AC-yard for minimal local disturbances, magnetic field studies according to ICNIRP norms for human exposure, and quantification of induced eddy currents in enclosures and buildings [3]. Fig. 15 is a close-up view of a simulated substation model that includes two medium voltage multi-level converters, four high voltage transformers and a total of 12 air core reactors. The example shows the computed reactor currents with the resulting eddy currents in the conducting converter building structure underneath the reactor stack.

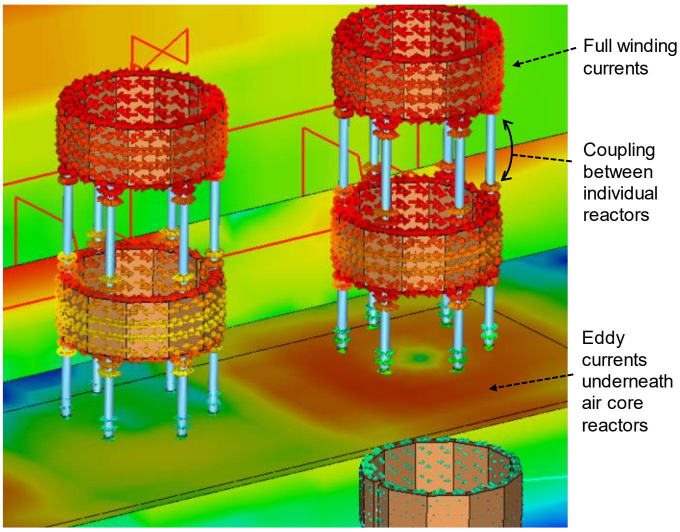

Fig. 15 Reactors on the roof of a substation installation with simulated winding currents and induced eddy currents underneath the reactors.

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