A link between EMTP-RV and FLUX3D for transformer energization studies

S. Dennetière, Y. Guillot, J. Mahseredjian, M. Rioual

Abstract-- This paper presents a programmed link between the electromagnetic transients program EMTP-RV and the finite element field solver FLUX3D. The model created in FLUX3D is driven from simulation designs in EMTP-RV. The test cases presented in this paper demonstrate that the coupling method is numerically robust and with sufficient accuracy. This approach benefits from EMTP advantages in modeling large scale networks and from field solver advantages for detailed representation of power transformer iron cores.

Keywords: EMTP, FLUX3D, interface, switching transients, transformer transients

I. INTRODUCTION

THe R&D Division of EDF performs since 1996 studies on transformer energizations, from the determination of palliative solutions for auxiliary transformers of power plants after a partial or total collapse of the network, to the reduction of stresses when energizing transformers of wind farms or those on hydraulic pumped-storage plants.

The energization of an unloaded power transformer may have undesirable effects on power quality and may damage the transformer.

For those purposes, the modelling of the transformer is a key issue, especially the phenomena involved in the iron core during energization. The transient modeling of transformer energization requires an accurate nonlinear model of the magnetic material and a detailed representation of the electrical network as presented in [1] - [3].

In most EMTP studies involving the energization of transformers, the transformer models are based on uncoupled single-phase units, to which a hysteretic model is added, in order to take into account the losses in the iron core (eddy current and iron losses). This model is also very useful for the representation of winding copper losses and can be efficiently used in EMTP statistical studies. It is however limited by the fact that it does provide a detailed representation of the iron core, from its geometrical and magnetic characteristics and therefore does not represent the coupling effect with high accuracy. Such a limitation will not affect simulation results in some cases, but may have a significant impact in other cases, depending on the connection type of the transformer windings.

A detailed representation of the iron core is needed to model the behavior of flux paths and saturation effects inside the core, the flow of fluxes inside and outside the transformer, especially in the case of five limb transformers. This representation is also useful to estimate the mechanical stresses generated by the flow of fault and inrush currents inside the transformer.

A field solver based on the finite element method (FEM) can accurately take into account the material nonlinearity, winding connections and material anisotropy. However, field solvers do not provide the variety of power system components needed for a large power network simulation with control systems, surge arresters and multiphase transmission lines. This paper is based on the idea of coupling (interfacing) two different modeling and computation approaches for a given simulation case and thus achieving higher precision as required. The interface applications are FLUX3D and EMTP-RV.

II. COUPLING ELECTRICAL CIRCUIT AND MAGNETIC FIELD SOLVERS

There are two different approaches for combining the solutions of field equations and circuit equations.

The first approach consists in developing a program that solves simultaneously field equations and circuit equations. The magnetic equations are solved using a formulation with the magnetic potential vector. The coupling is obtained by the conductor current expressed in terms of current density and flux linkage found from the potential vector (see [4], [6]-[8]). The time-dependant differential system resulting from coupling is solved with step-by-step numerical integration. To take into account the magnetic and electric nonlinearities, a Newton-Raphson iterative procedure is used. This approach is disadvantaged for the simulation of complex and large power networks since it provides a limited number of network component models and is inherently less efficient for classical network models.

The second approach consists on interfacing separate specialized codes for optimizing performance and precision, and for benefiting from investments in established and validated libraries.

This paper is based on the second approach: it presents and tests a DLL (Dynamic Link Library) based interface between the Electromagnetic Transient Program EMTP-RV and the field program FLUX3D.

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Simulation variables are exchanged between the field and circuit models with a one time-step delay. This principle is not new and is similar to [9] and [10]. The interest of this paper lies in the fact that this connection is general: not only currents and voltages can be exchanged between the field solver and EMTP but also switching times, fluxes and mechanical forces. The paper is also contributing a programmed interface with FLUX3D and EMTP-RV applications.

III. SIMULATION OF POWER TRANSFORMER TRANSIENTS

A. *Network modeling in FLUX3D*

A 3D finite element method coupled to circuit equations is presented in [5]. In [7] it is proposed to generalize this method for the case of solid conductors. The proposed formulation takes into account multiple connected electrical circuits for nonlinear solid conductors. To deal with magnetic saturation the Newton-Raphson procedure is used along with a prediction procedure.

An example of power transformer energization with circuit equations is presented in Fig. 1. The Wye/Delta transformer is connected to a Thevenin equivalent circuit.

The number of circuit (power) components is limited.

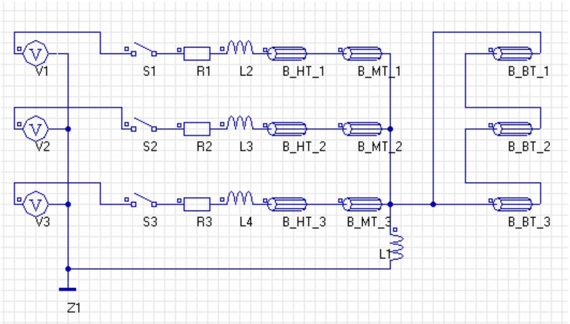

Fig. 1 Finite element method coupled to circuit equations in FLUX3D

B. *Transformer modeling in EMTP*

Two types of transformer models are available in EMTP: 3-phase transformer model based on uncoupled single phase units and 3-phase transformer model with internal coupling. The representation of single-phase N-winding transformers for steady-state and transient studies is straightforward [11].

Three-phase transformer models are usually based on the physical concept of representing windings as mutually coupled coils. The impedance or admittance matrices of the coupled coils can be easily derived from commonly available test data [12]. The models can be used for many types of studies as long as the frequencies are low enough so that the capacitances in the transformer can be ignored.

Studies of energization of unloaded transformers for power restoration purposes require detailed models that account for the behavior of flux paths, saturation effects inside the core and forces inside transformers. Transformer models in EMTP are not suitable for these studies.

IV. THE EMTP / FLUX3D INTERFACE

A. *Basic principles*

A DLL based interface has been chosen to couple EMTP-RV with FLUX3D. EMTP-RV drives the complete simulation through the EMTP-RV graphical user interface (Fig. 2).

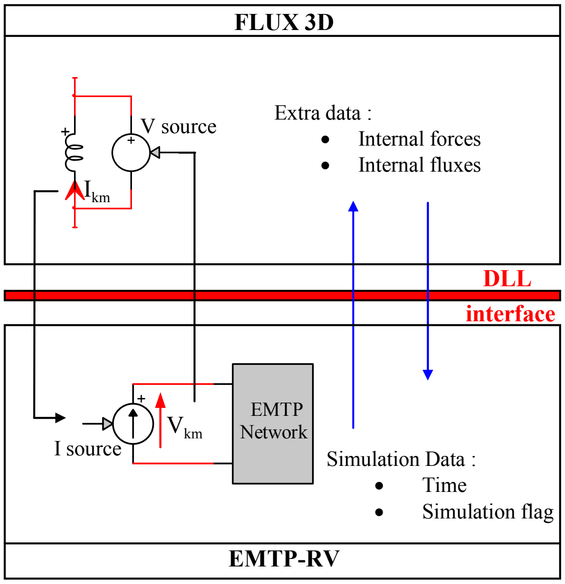

Fig. 2 Coupling principle for each phase of transformer

A FLUX3D coil is represented in EMTP by a controlled current source connected between two nodes. At each time-point EMTP solves the network equations and finds unknown voltages. The branch voltages V_{km} of controlled current sources are sent to FLUX3D. EMTP also sends the time variable. The controlled voltage sources are updated at this step with V_{km} values and a FEM simulation is performed. At the end of the simulation currents flowing in each coil are available on EMTP side in addition to extra data such as tank temperatures, internal fluxes and internal forces. The interface enables to simulate transformers with any number of phases.

A flag signal transmitted using EMTP control blocks to FLUX3D enables or disables this communication process. EMTP calls the field program only when it is required: at every time-point, at every *n*th time-point or when a certain user-defined condition is reached. An example of condition could be the value of flux derivative exceeding a given threshold. The overall interface is designed to optimize computational speed.

B. *Time-step delay*

The approach presented above introduces a time-step delay between field calculations and the EMTP side solution. The current injected in the EMTP network at time t has been calculated in FLUX3D at $t\text{-}\Delta t$. Experiments indicate that this approach is acceptable in most of cases. Although it will not give the exact solution, the error can be minimized by selecting smaller time-steps. As explained in [13] such an interfacing method is not fully accurate, but numerical stability is preserved. Satisfactory results are obtained with smaller time-steps, which can be 10 times smaller than the time-step size required for simultaneous solution capable solvers [9].

The computational burden is also strongly related to the performance of the FLUX3D software.

C. *Switching times and floating nodes*

Initially the interface has been developed to simulate simultaneous switching events in phases a, b and c. In reality switching events are not simultaneous: the coupling principle presented in Fig. 2 is only valid for the 1-phase or 3-phase uncoupled cases. When a 3–phase coupled transformer is energized, the first switching event produces magnetization inside the transformer and generates induced voltages on open phase poles of breakers. These induced voltages have a significant impact on over-voltages that appear when the open poles of breakers close. To take into account this statement the above interface has been modified as follows, for each coil:

- before switching: the coil simulated in FLUX3D is modelled in EMTP as a voltage source. The induced voltage between the two nodes of this coil is calculated at each time-point by the field program and transmitted to EMTP. The current flowing in this coil is zero, this data is transmitted to the field program.
- after switching: the coil is modelled as a current source in EMTP. Data is now transmitted as in Fig. 2

V. TEST CASES

A. *Validation on a simple case*

The objective of the first test case is to validate the coupling method. This case consists in simulating the energization of a 3-phase transformer connected to an RL impedance and a voltage source. The 3 phases are energized simultaneously. Fig. 3 presents the circuit in EMTP-RV.

The FLUX3D transformer model is represented in the GUI by a 3-phase block. The control pin is used to activate the field calculation (always activated in this case, C1>0). Internal fluxes and forces are available through a bundle connection. By clicking on this block users can fill a form to specify simulation options of the field solver and internal measures that will become available through bundle pins.

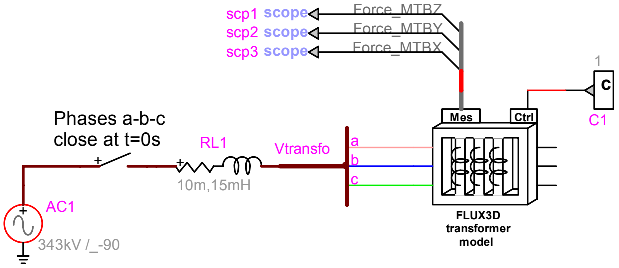

Fig. 3 First test case in EMTP-RV

The transformer modelled in FLUX3D is a 400/225 kV transformer, 600 MVA, 5 limbs, YnD11. The B(H) characteristic of the magnetic circuit is nonlinear. A first order finite element mesh of 12,000 nodes is used. A view of the FLUX3D model is presented in Fig. 4 (the mesh of the magnetic circuit and coils).

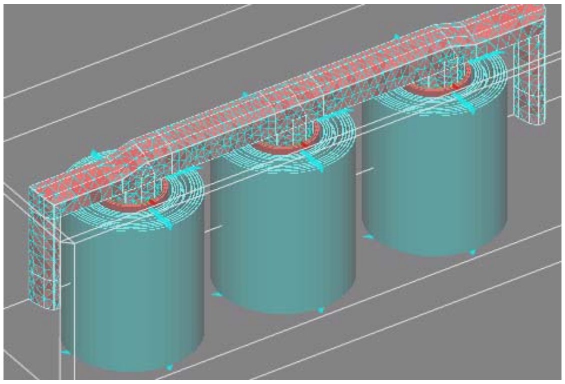

Fig. 4 Representation of the magnetic circuit and coils in FLUX3D

As shown in Fig. 5 an electrical circuit is coupled to the transformer model in FLUX3D. This circuit contains 3 voltage sources controlled by EMTP as follow :

- $V_1(t)=V_{transfo\ a}(t)$
- $V_2(t)=V_{transfo\ b}(t)$
- $V_3(t)=V_{transfo\ c}(t)$

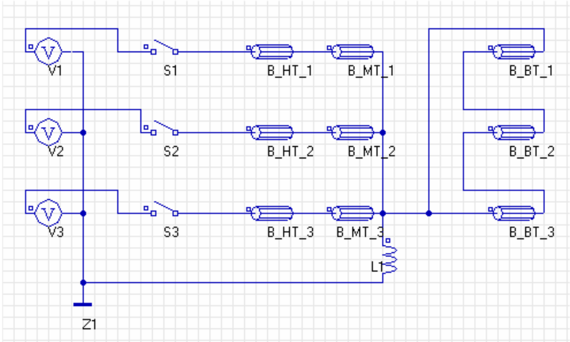

Fig. 5 Description of the electrical circuit in FLUX3D

This EMTP/FLUX3D simulation is validated with a FLUX3D simulation in which circuit equations are solved simultaneously with field equations. This circuit used for validation is presented in Fig. 1. RL1a, RL1b and RL1c in Fig. 3 are defined in Fig. 1 as R1-L2, R2-L3, R3-L4.

The phase a inrush current is presented in Fig. 6. Current values calculated by FLUX3D alone (circuit equations are solved simultaneously with field equations) are compared against those calculated by the EMTP/FLUX3D interface scheme. Maximum relative error is 3% with Δt=0.5 ms. The error is due to the one time-step delay between EMTP solutions and field calculations. The error increases when the value of the network impedance increases.

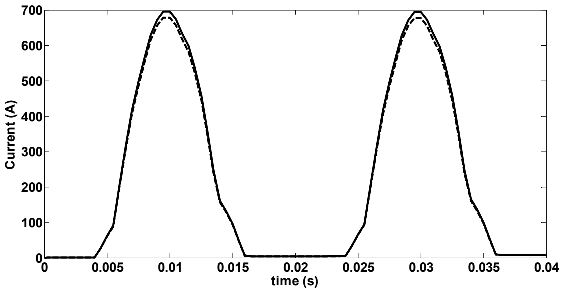

Fig. 6 Inrush currents, solved with FLUX3D (solid) and FLUX3D/EMTP (dashed line)

Magnetic induction in the transformer is available at each time-point during the EMTP/FLUX3D simulation.

B. *Real case, EHV 400 kV network*

A high-level view of the selected test case is shown in Fig. 7. The test case studies the energization of a 600 MVA autotransformer through a 180 km long line. This target transformer, modeled in FLUX3D, is the same than the one presented in the first test case.

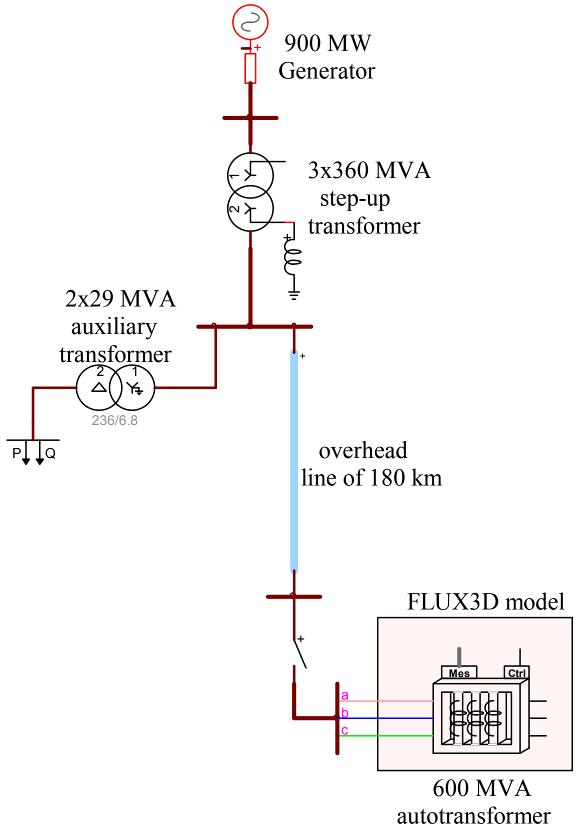

Fig. 7 Single line diagram of the industrial case

The methodology applied to model the rest of the network is explained in [1]. The generator at the sending end is a 900 MW machine, which is modeled as an ideal source behind its substransient reactance.

The long line is modeled using pi-sections. The number of PI cells has been chosen in order to represent correctly the exact impedance under the 4th harmonic which is the resonance frequency of this network. Step-up and auxiliary transformers are modeled by a set of one-phase transformers where the leakage reactances, the copper and core losses and the saturation are taken into account. The time-step for this test case is 0.1 ms. It has been chosen to correctly represent over-voltages due to harmonic inrush currents.

Switching times are: t=15.8 ms on phase a, t=0 ms on phase b, t=10.2 ms on phase c.

This EMTP/FLUX3D simulation is compared against an EMTP simulation in which the autotransformer is modeled by a set of 3 one-phase transformers. This is a classical model of one-phase transformer with nonlinear magnetization branch. The method of modeling used in this EMTP simulation is presented in [1] and has been validated by on site tests.

Voltages at the breaker are shown in Fig. 8, Fig. 9 and Fig. 10. Even if coupling between phases is not modeled in the EMTP autotransformer model, the EMTP/FLUX3D coupled-scheme results are very close to the results obtained with the simple EMTP modeling.

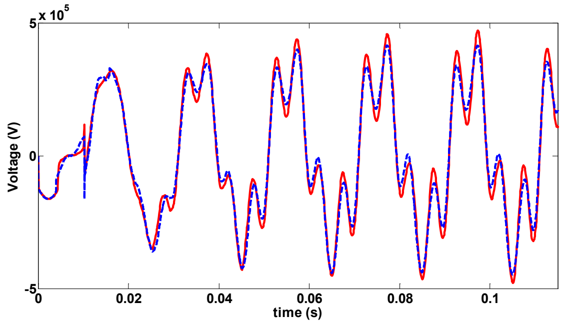

Fig. 8 Phase-a voltage, EMTP/FLUX3D solution (solid line) and EMTP solution (dashed line)

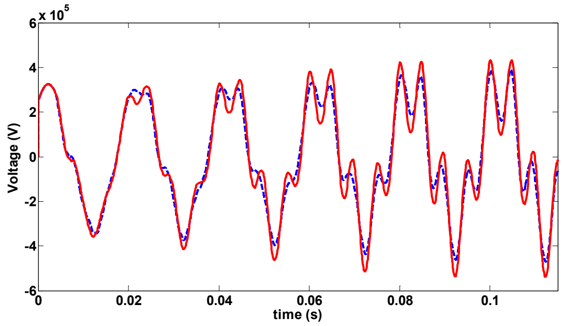

Fig. 9 Phase-b voltage, EMTP/FLUX3D solution (solid line) and EMTP solution (dashed line)

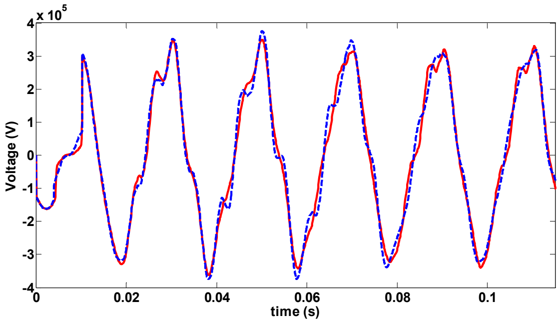

Fig. 10 Phase-c voltage, EMTP/FLUX3D solution (solid line) and EMTP solution (dashed line)

At each time step the behaviour the flux patterns in the magnetic core can be visualized. Fig. 11 shows the parts of magnetic core where the magnetic flux saturates at t=20 ms.

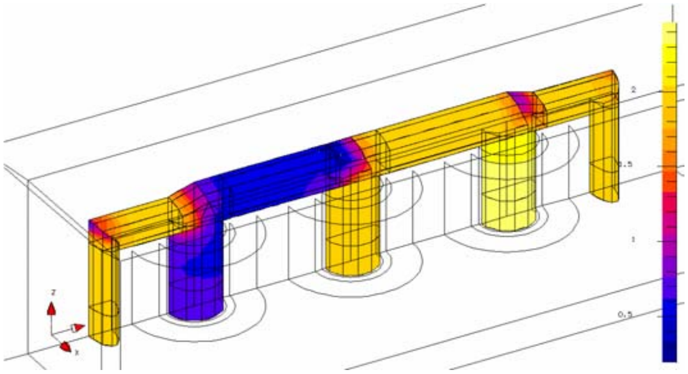

Fig. 11 Flux circulating in the magnetic core (3rd limb highly saturated at t=25 ms)

Mechanical sensors are used in the FLUX3D model (half cylinders around main limbs in Fig. 11) to estimate mechanical forces applied on coils. Fig. 12 shows internal fluxes in 1st and 5th limbs.

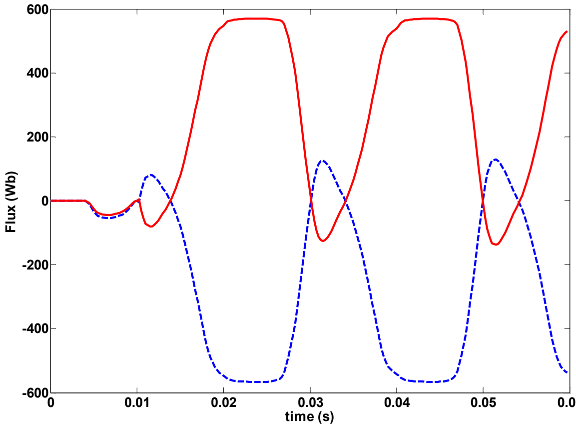

Fig. 12 Internal fluxes in 1st limb (dashed line) and 5th limb (solid line)

VI. CONCLUSIONS

This paper has presented the implementation of a link between the field program FLUX3D and the electromagnetic transients program EMTP-RV. This approach benefits from EMTP's advantages in modeling large scale networks with a large library of network components and from field solver capabilities in taking into account detailed representation of internal transformers behavior for flux paths and mechanical forces.

The capability to calculate mechanical stresses and internal fluxes inside transformers is important under some operating conditions. Transformers tank internal thermal information may be derived as well. This approach may also be applied to model surge arresters, circuit breakers and electrical machines.

The proposed interface between EMTP-RV and FLUX3D constitutes a useful tool for utilities and manufacturers, when equipment sizing is considered for new equipment, but also for asset management on the existing network.

VII. REFERENCES

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VIII. BIOGRAPHIES

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