Electromagnetic Simulation: Successful Applications and Future Challenges

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Abstract: A series of case studies is used to demonstrate how state of the art electromagnetic simulation methods are exploited in the design and analysis of industrial devices, including electrical machines and transformers, power cable lengths and terminations, magnetic signatures in the marine environment as well as high frequency devices.

Keywords: Finite Element Analysis, Finite Difference Time Domain, Method of Moments, electromagnetic simulation, electrical machines, magnetic signatures.

1. Introduction

Electromagnetic simulation is today an integral part of the design process in industry. The advent of computer technology and numerical methods over the past 20 years has enabled designers to finalise a design with a great degree of confidence, in many situations without the need of prototyping.

The aim of this paper is to review state of the art electromagnetic simulation methods, including Finite Element Analysis (FEA), Finite Difference Time Domain (FDTD) and Moments, concentrating on a series of case studies that demonstrate how these methods are exploited in the design and analysis of devices for industrial applications.

2. Modelling Power Systems Devices

2.1 Power Cables modelling

The electromagnetic fields generated from energised power circuits and transformers are of concern to designers, as they form part of any study on the impact of the power network infrastructure on the environment and/or neighbouring switchgear.

Fig. 1 shows a plot of the magnetic vector potential, **A**, around an energised XLPE twin-trefoil transmission cable arrangement. A cable shield, in the form of an aluminium sheet placed above the cable arrangement, was included to reduce the generated magnetic field from 16.5 μT to a maximum of 6.76 μT at ground level. This is due to the fact that eddy currents opposing the field that caused them, are generated in the highly conductive aluminium sheet.

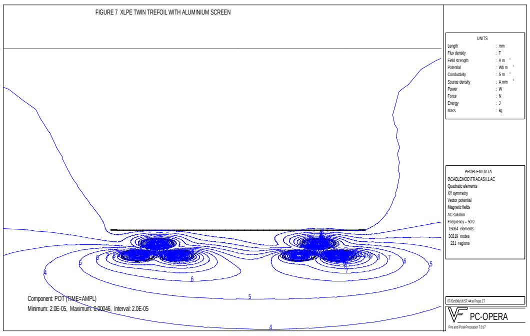

Fig 1. Magnetic Vector Equi-Potential contours in shielded Twin Trefoil Cable arrangement.

Finite Element simulation helped to establish the correct dimensions and positioning of the shield to keep the magnetic field at the required level on the ground [1]. The same model was used to evaluate cable parameters, ie. the self and mutual impedance.

2.2. Power Transformer Modelling

Three-dimensional FEA can be used for the design of 3-phase transformers. Electromagnetic simulation can successfully evaluate the flux levels at varying current levels, including saturation and eddy current effects.

Furthermore, the location of distribution transformers is often problematic. The effect of stray magnetic fields on sensitive neighbouring electrical equipment needs to be quantified. Prediction of the stray field is not simple due to:

(i) Magnetic saturation in the transformer yoke increasing the stray field

(ii) The effectiveness of a transformer tank wall acting as a shield, due to both the magnetic behaviour of the wall and the induced eddy currents in it.

The presence of eddy currents in the tank also presents a problem to the designer. How close can the wall be to the transformer without excessive heating? The OPERA-3D/ ELEKTRA eddy current analysis package has been used to examine a 3-phase, 800 KVA distribution transformer.

Fig. 2 shows results from non-linear analysis of the distribution transformer and associated conducting tank. The program was used to successfully predict the flux density levels in the transformer as well as the reduction in fields around the transformer, resulting from the addition of a conducting tank [1].

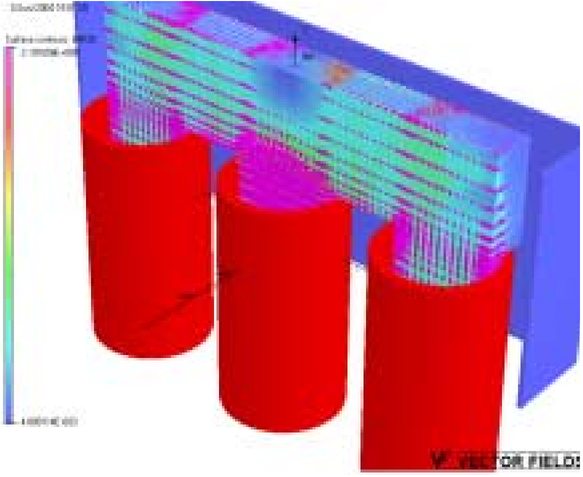

Fig. 2. Magnetic fields in transformer core & tank.

2.3 Modelling of Cable Terminations

An advanced CAD package customised for the design of electric insulating components, was recently developed [2]. The environment allows better in-house design of cable junctions and terminations without prototyping and hence reduces costs of new product development.

Fig. 3 shows the electric potential in a LV cable termination, obtained using the OPERA 2d/LD (Lossy dielelctric solver) which can model materials with lightly conducting & dielectric properties.

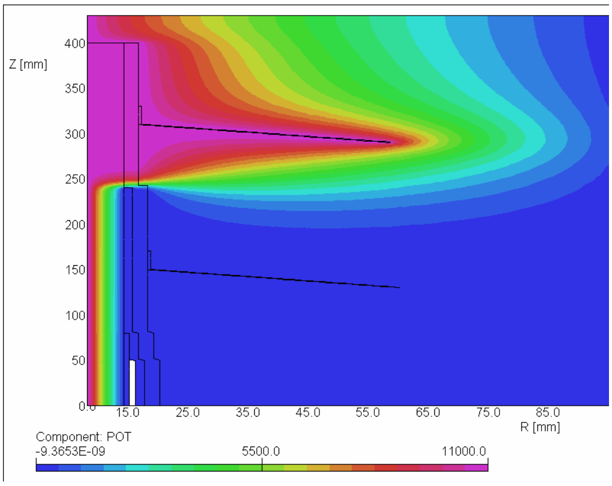

Fig. 3. Contours of electric potential in region of a LV Cable Termination.

The conductivity of the materials surrounding the live conductor cause a significant re-distribution of the potential around the termination. The insulation of the cable is only slightly conducting and therefore, moving radially out towards the 0kV conductor, a significant voltage drop is recorded in this material. However, this is only true along the length of the 0kV conductor. The conductivity of the stress control material can dictate the voltage distribution further up the termination, and the correct value can result in a smooth voltage distribution and hence lower voltage stress. This information is crucial to the designers of cable terminations, as it dictates the steady-state withstand voltage and life span of the Termination.

The maximum voltage withstand in a cable termination is determined by applying the standard impulse voltage function to the conductor using the OPERA-2d/LD solver in transient mode.

3. Modelling Demagnetisation

A recent collaborative project between Vector Fields Ltd and Magnequench has lead to the development of the de-magnetisation solver [3]. OPERA-2d/DM is a transient analysis program that has been developed to model the magnetisation process for hard magnetic materials. During non-linear analysis OPERA-2d DM can use a virgin BH curve for material magnetisation and then secondary 'demagnetisation' BH curves as the field decreases. In non-linear materials specified with demagnetisation BH-curves, the maximum field in each element (value and direction), is monitored. When the field in an element drops below the maximum field, a demagnetisation BH-curve is used for that element, rather than the magnetising BH data. The maximum field achieved in each element is stored in the solution file. Fig. 4 shows the magnetisation of two ring segments, near the peak of the applied magnetisation pulse:

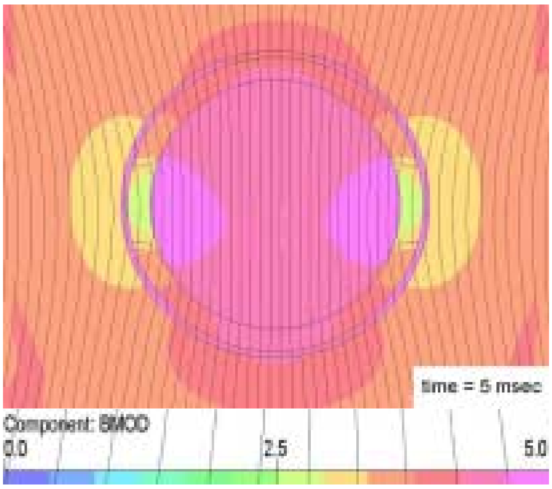

Fig. 4. Magnetisation of two ring segments. (Model Courtesy of Magnequench).

OPERA-2d/DM can analyse the response of a system to multiple drive functions (sinusoidal, dc or functional) and successfully predict the distributed magnetisation (magnitude and direction) in permanent magnets while accounting for eddy current effects in the device. The realistic distribution can be transferred to an OPERA-2d 'application model' for the static and dynamic electromagnetic analysis of the device in which the magnets are to be used. The aforementioned ring segment magnets were introduced in a permanent magnet DC appliance motor and the resulting field distribution, at zero armature current, is shown in Fig. 5.

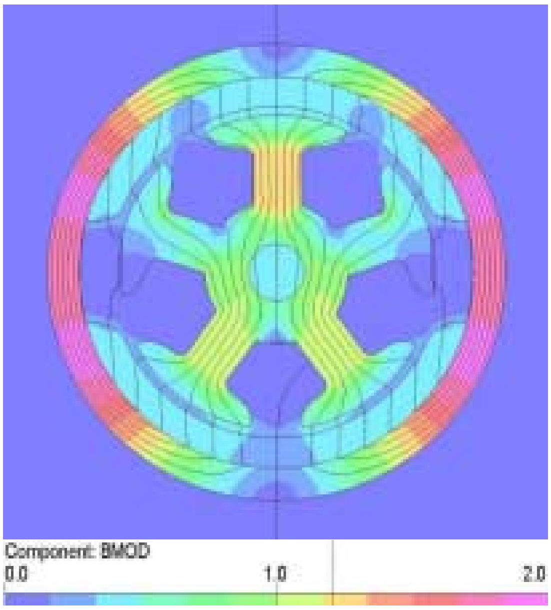

Fig. 5. Ring segment magnets, as part of a PMDC machine (Model Courtesy of Magnequench).

4. Dynamic analysis of rotating machines

Motional analysis is required when the response of a system, such as an electric appliance drive, coupled to a mechanical load must be examined. Motion must also be considered if fault analysis or harmonic evaluation on a synchronous machine is needed. Special machines (such as a 1-phase synchronous generator or IM) need rotational analysis to accurately predict their performance.

The Rotating Machines program OPERA-2d/RM is a transient eddy current solver, extended to include the effects of rigid body rotation. The solver provides for the use of external circuits and coupling to mechanical equations.

Fig. 6 shows the voltage profile in the three phases of a 4-pole synchronous generator under open circuit conditions, as obtained using the

Rotating Machines solver. Upon the subsequent application of a 3-phase symmetric fault, OPERA-2d/RM predicts high current levels in the 3 phases before the envelope of these decays to the steady state short circuit value according to an exponential law, as shown in Fig. 7. Fig. 8 shows the flux distribution in the machine under short circuit conditions, illustrating the armature and field excitation cancellation.

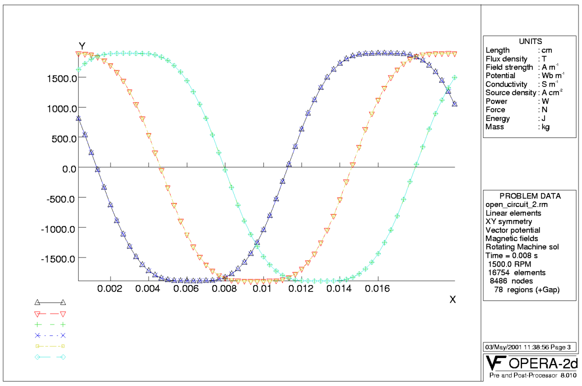

Fig. 6. Open Circuit voltage profile.

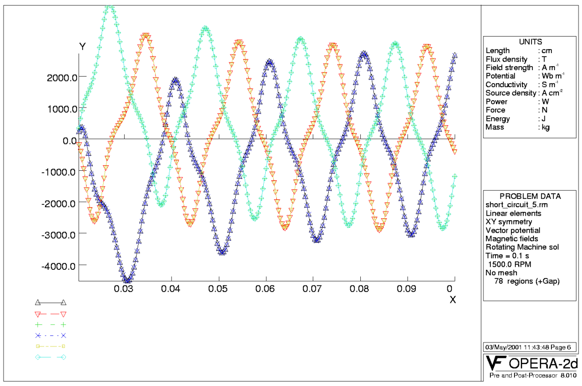

Fig. 7. Short Circuit Current distribution

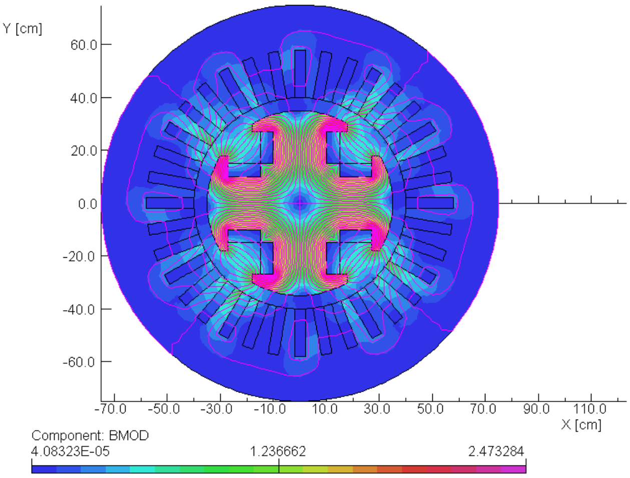

Fig. 8. Flux distribution in a 4-pole synchronous generator, illustrating armature/field cancellation.

The rotating machines solver can also be used to model the transient behaviour of a generator 'going on load'. Fig. 9 shows the voltage output on a single-phase generator, initially on open-circuit. Upon the sudden application of a resistive load, the load angle of the machine changes significantly and a voltage drop at the machine terminals is recorded.

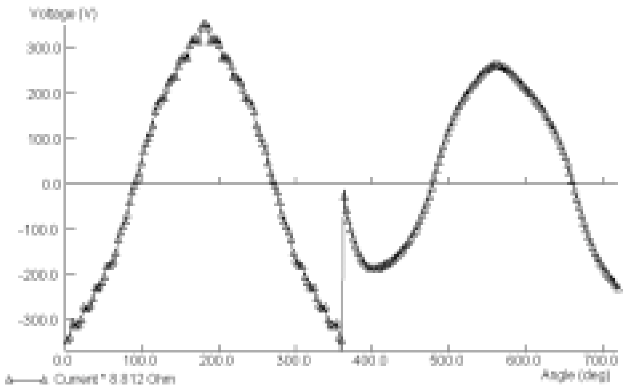

Fig. 9. Load switching in a 2-pole 1-phase synchronous generator.

Recent developments in OPERA-2d/RM have resulted in the capability to couple a complex load characteristic, which can be speed and/or time dependent to an electronically controlled motor, such as a BLDC with chopper control and position sensing or an inverter fed induction motor with variable excitation frequency. Fig. 10 illustrates the start up characteristic of an induction motor, coupled to a speed dependent (fan) load.

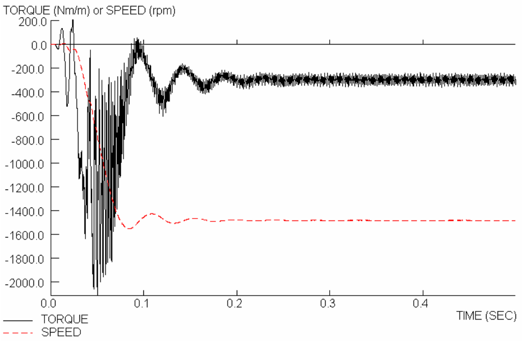

Fig. 10. Induction motor coupled to a fan load.

5. Magnetic Signatures in a Marine Environment

The study of electromagnetic fields in a marine environment has a long history. It has only been in recent times, with the development of faster computers and efficient algorithms, that numerical simulations of these fields has become possible.

The study of ship generated magnetic, electric and ultra-low/extremely low frequency electromagnetic fields (signatures) has been driven by the defense sector. The characterization of these signatures is of concern in the areas of mine and anti-submarine warfare. There are three major shipboard field sources of interest.

5.1 Ferromagnetic

The ferromagnetic signature arises from the presence of the steel structure of the ship in the earth's magnetic field. In naval vessels the signature is also affected by degaussing coils which aim to reduce the signature by producing a canceling field. Finite element techniques have proven to be a successful approach for modeling the characteristics of these fields. Fig. 11 shows a ship structure which has been analyzed using the OPERA-3d/TOSCA solver. TOSCA is able to deal with the complex geometries and degaussing coil arrangements and can account for the non-linear magnetic properties of the materials.

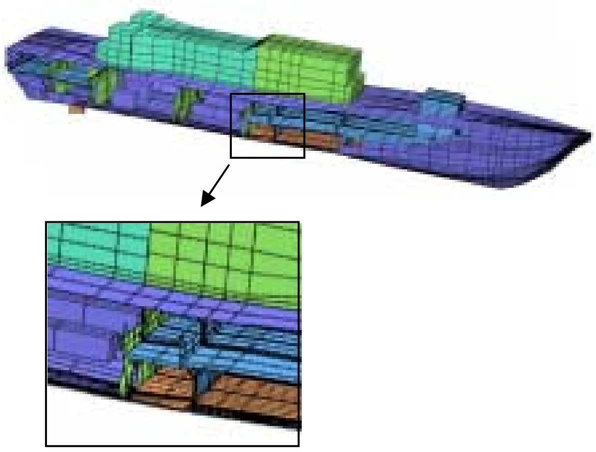

Fig. 11: FEA model of a typical ship geometry showing superstructure and internal detail

5.2. Eddy-current

The eddy current signature also arises from the steel structure (as well as other metallic components) of the ship in the earth's fields. In this case, however, it is the motion of the ship that results in eddy currents forming in the conducting hull and superstructure of the ship.

Again, finite elements have proven to be a successful approach for simulating this type of problem. The model geometry shown in Fig. 11 was analyzed using the ELEKTRA-SS solver. The accuracy of the simulation can be seen in Fig. 12 which shows a comparison between the measured and the calculated results, along the keel line a set distance below the ship.

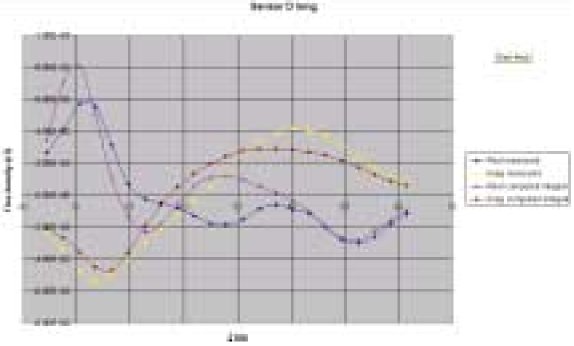

Fig. 12. Comparison of ship signature predicted in ELEKTRA-SS analysis with measurement.

One of the recent advances in the ELEKTRA solver is the use of edge based elements. In Table 1 the improvements in solution time and accuracy, which lead to detailed analysis, can be noted.

Formulation	*Equations*	*Iterations*	*Final relative change*	*CPU time (sec)*
Nodal	171224	171225	0.27E-05	111181 (31 hr)
Edge	378304	3904	0.63E-08	4447 (1.25 hr)

Table 1. Comparison of solution times between ELEKTRA-SS Nodal and ELEKTRA-SS Edge for ship analysis of Figure 11 and Figure 12.

5.3 Corrosion related electric and magnetic

The high salinity of seawater makes it a corrosive medium for electrochemically dissimilar materials. For a typical steel hulled ship with a bronze alloy propeller, this means that corrosion is a significant problem. Numerical modeling is important to help optimize the anti corrosion systems, and for naval vessels, to balance this against required signature targets.

For stand alone analyses of the corrosion fields, boundary element methods are commonly used with great success. With the move towards combine signature analysis, however, it is likely that finite elements will become increasingly more important in this area of study.

6. High Frequency Electromagnetic Analysis

High frequency electromagnetic analysis can be performed using different solution methods, depending on the application. A Finite Element Analysis solver, such as CONCERTO/Soprano, will provide analysis of propagation effects in waveguide components as well as characterize resonant devices.

The Finite Difference Time Domain Method (FDTD) is employed in CONCERTO/QuickWave, for the fast and accurate simulation of a wider range of high frequency devices including antennas, filters as well as waveguides and resonators.

CONCERTO/Clasp is a versatile method of moments electromagnetic modeling tool that can extend high frequency design and analysis to antenna coupling, EMC as well as radar signature, as shown in Fig. 13.

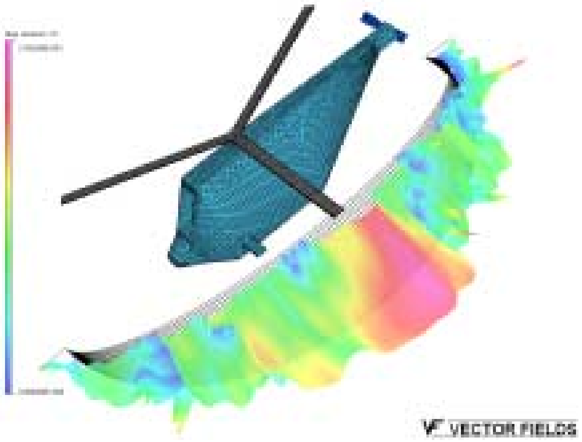

Fig. 13. RCS of representative helicopter.

CLASP can be used to analyze antenna installed performance, including radiation patterns and coupling to other bodies. Analysis of both mono- and bi-static RCS can also be carried out.

Conclusions

A series of case studies was used to demonstrate how state of the art electromagnetic simulation methods are exploited in the design and analysis of industrial devices, including electrical machines and transformers, power cable lengths and terminations, magnetic signatures in the marine environment as well as high frequency devices such as antennas and EMC.

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