Abstract — The paper presents a global Finite Element Method model developed to understand and quantify the complex phenomena of energetic transfer and overpressure taking place within a transformer vessel during and after a short-circuit. The goal of the model is to design an efficient system able to protect Power Transformers against explosion and resulting oil fire. The model presentation and comparison with experimental results will be developed in the paper.

Keywords — MTH Model, Explosion and Fire Risk, SERGI TRANSFORMER PROTECTOR.

I. INTRODUCTION

Transformers are considered by Corporate Risk managers and Insurances as the most critical equipment inside plants because of the large quantity of oil in contact with large high voltage elements. A one-year Internet search led to the discovery of more 730 transformer explosions in the USA. Many experts anticipate that the number of failures will increase significantly in the near future, from 1% in 2001 to 2% in 2008. In addition, the shorter lifetime of new transformers will sharply increase this rate after 2008.

The Norm IEC 76 only includes basic electrical measurements and does not cover mechanical design or protection. This weakness, in addition to the globalisation market, has opened the door to a disturbing drop in the quality of new transformers. By comparison, pressure vessels have to comply with adequate rules and controls. Such directives do not exist for transformers, which are obviously more dangerous. In most vessel explosion, the electrical protections are working and tripping transformers normally. The efficiency of the Electrical Protections is therefore related to the breaker tripping speed. Unfortunately, the actual technology is insufficient to avoid vessel blast in case of a major short-circuit.

A perfect knowledge of the transient behaviour of transformers in response to an electrical fault is required to prevent them against explosions and fires [1–6].

II. MTH MODEL PRESENTATION

The MTH Finite Element Model described in this paper is a global physics approach initially developed to study and to quantify the energy transfer phenomena and pressure increase mechanisms in oil capacities during and after an electrical fault. Besides, the model can be used as a computational tool to design efficient protection systems able to de-pressurise the transformer vessel in order to avoid explosion and the resulting oil fire.

To deal with all physical and chemical phenomena occurring within the transformer vessel a system of four coupled equations is solved by a way of analytical and numerical FEM environment.

A. Magneto-dynamic Equation

The first equation to solve due to Maxwell's equation, in term of vector potential is the following:

$$\nabla \times (\nabla \times A) + j\sigma \omega A = \mu_0 \frac{\partial}{\partial t}$$

(1)

Considering the complexity of the coil geometry and the number of conductors, we preferred to use an analytical approach instead of the Finite Element method. Using the double series Fourier approach, the vector potential $A$ is [7]:

$$A_z = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} A_{ji} \cos(\alpha_i x) \cos(\beta_j y)$$

(2)

The calculation of the distribution of the eddy currents is made by considering that the magnetic field is uniform inside each conductor. By a traditional technique of separation of variables one can calculate the distribution of the eddy currents in each conductor using the escape field previously calculated.
Losses due to eddy currents (Jf) and Joule effect (Ptot) are obtained as:

\[ J_f(x,y) = \frac{(i+1)H_y}{\delta} \frac{\operatorname{sh}(\frac{(i+1)}{\delta} x)}{\operatorname{ch}(\frac{(i+1)}{\delta} a)} + \frac{(i+1)H_x}{\delta} \frac{\operatorname{sh}(\frac{(i+1)}{\delta} y)}{\operatorname{ch}(\frac{(i+1)}{\delta} b)} \]

\[ P_{\text{tot}} = \frac{1}{2\sigma} \int \int J_{\text{Source}}^2 \, dS + \frac{1}{2\sigma} \int \int J_{\text{Foucault}}^2 \, dS \]  

**B. Heat Transfer Equation**

The thermal sub model resolves the partial derivative equations in a Cartesian geometry is the following:

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p v \cdot \nabla T + \nabla \cdot ( - k \nabla T ) = Q \]

Where \( \rho \) is the Oil density, \( C_p \) and \( k \) are respectively the heat capacity and the thermal conductivity of considered materials, \( v \) is the oil velocity vector, and \( Q \) is the thermal source density (Joule losses).

Once resolved, the differential equation determines the temperature \( \theta \) of the elementary oil volume versus time. The resolution also takes into consideration the vessel and winding geometry. It is therefore possible, thanks to a tight meshing, to determine the oil temperature at any point of the vessel.

**C. Navier-Stockes Equation**

By associating the Navier-Stockes equation to the temperature equation, it is possible to determine the oil pressure and velocity at any point of the vessel. The hydrodynamic sub model resolves Navier-Stokes equations and mass conservation equations in Boussinesq approximation as:

\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \mathbf{g} + \eta \Delta \mathbf{v} \]

Where \( \mathbf{v} \) is the Oil velocity, \( \rho \) is the Oil density, \( \eta \) is the Oil dynamic viscosity, and \( p \) is the Volume Oil Pressure from gravitational strength and drainage.

**D. Real Gas and Arrhenius Laws [8-11]**

The produced gas pressure is obtained by associating the real gas and Arrhenius Laws (7 and 8 respectively)

\[ p_2 + n^2 \frac{a}{V} (V - nb) = nRT \]  

\[ k = Ae^{\frac{-E_a}{RT}} \]

Where \( n \) is the Gas Mole Number, \( V \) is the Oil Volume Corruption, \( T \) is the Oil Surface Temperature, \( p_2 \) is the produced Gas Pressure, \( R \) is the Ideal Gas Constant, \( a \) and \( b \) are Gas Generation Constants, \( k \) is the Reaction Speed, \( A \) is an Exponential Factor, and \( E_a \) is the Gas Activation Energy

The Arrhenius law is especially used to determine the nature and quantity of generated gas. The gas temperature is extremely high at the instant of generation, so the thermal expansion should be taken into account. The result of the pressure rise must also take into consideration the oil static and dynamic pressure.

**E. MTH Model Illustration and Validation**

In order to illustrate the MTH applications, we chose to study the consequences of an inner short-circuit in a 20 MVA transformer equipped with one OLTC.

Figure 1, shows the local temperature evolution for several times: 55, 85 and 105 milliseconds after an inner short-circuit. One can note that when circuit breaker trips, 85 milliseconds after short-circuit, local temperatures are mainly over 930 K (660°C).

The result of the local pressure integration in the whole vessel, for the same transformer and fault conditions, is given in figure 2. The vessel pressure is represented in the cases of Breaker failure, non-tripping, and Breaker tripping with 86 milliseconds inertia.

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**Fig.1. Temperature evolution inside a 20 MVA transformer after a short-circuit.**

**Fig.2. Pressure evolution inside a 20 MVA transformer after a short-circuit.**

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**III. EXPERIMENTAL VALIDATION OF MTH MODEL**
Experimental checks were carried out in collaboration with a French transformer manufacturer, using a 160 KVA post transformer. Results concerning both temperature and pressure were previously published [2-3]. The Table here above gives an idea of the MTH model precision for temperature calculation. Two loads conditions are represented: Steady state and Overloaded state.

Today, the MTH Model is an invaluable aid to the design and sizing of the transformer explosion and fire prevention system developed by SERGI and known as TRANSFORMER PROTECTOR.

### Table 1: Comparative Analysis of the Calculated and Measured Temperatures.

<table>
<thead>
<tr>
<th>Transformer State</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated</td>
</tr>
<tr>
<td>Steady state</td>
<td>LV = 69.1</td>
</tr>
<tr>
<td></td>
<td>HV = 65.5</td>
</tr>
<tr>
<td>22 % overload state, during 3 hours</td>
<td>LV = 78.4</td>
</tr>
<tr>
<td></td>
<td>HV = 72.3</td>
</tr>
</tbody>
</table>

### IV. SERGI PROTECTION SYSTEM

The SERGI TRANSFORMER PROTECTOR is a new concept that can be applied to all transformers from 100 kVA.

The SERGI TRANSFORMER PROTECTOR enables to:

- Depressurise tanks within milliseconds;
- Avoid contact between air and the evacuated explosive gases;
- Stop the explosive gas production by injecting nitrogen;
- Channel the gases far from the transformer environment to a remote area where they can burn safely;
- Quickly secure the transformer for a safe intervention.

The patent SERGI TRANSFORMER PROTECTOR is based on fast Rupture Disk opening and a Depressurisation Chamber which facilitates the quick depressurisation.

The Rupture Disk is a device intended to prevent overpressures generally in chemical and petrochemical applications.

The Rupture Disk goal is to protect systems from mechanical failures, chemical reactions and internal blasts. The disks are available in various materials, sizes, and configurations.

The Rupture Disks manufactured for the TRANSFORMER PROTECTOR are made of stainless steel and dimensioned for different pressure sets. The TP Depressurisation Set is generally located on the upper part of the transformer vessel.

The main parameter to control is the opening time. In fact, to avoid vessel explosion for the worst cases, the SERGI Rupture Disk had to be fully opened in a matter of one millisecond. This result was achieved after a large number of Rupture Disk tests calculations and simulations, which were necessary to find the best design to avoid transformer explosion for severe short-circuits.

Figure 8-10 illustrate the strong relation between the Decompression Set size and the capability of the SERGI Protection system in term of prevention against explosion and fire for different faults severity.

The Simulations are carried out for a single-phase, step up, located downstream of a 450 MVA generator:

- Nominal Power: 150 MVA
- Primary voltage: 18 kV delta
- Secondary voltage: 133 kV L-N
- Impedance: 15.5 %
- Cooling: Forced Oil, Water cooled
- Dimension: 121" diameter, 156" high
For this study, a 0.8 bar set point depressurisation pressure has been settled. Rupture Disks therefore split open at the calibrated pressure and release the excess of fluid.

![Fig.7. 150 MVA Transformer winding meshing](image)

![Fig.8. SERGI Protection System analysis for different Decompression Set sizes after a short-circuit of 34.4 kA.](image)

![Fig.9. SERGI Protection System analysis for different Decompression Set sizes after a surge of 118 kA.](image)

V. CONCLUSIONS

The MTH model initially developed to understand the physicals phenomenon in power transformers following electrical faults (short-circuits, electrical arching, lightning destroy ... ) and to quantify their resulting mechanical consequences is today a powerful CAD tool used for transformers design and prevention against explosion and fire. The MTH has been used to design a reliable device safety, called TRANSFORMER PROTECTOR (TP), which allows to make safe the transformer and to preserve the environment. The TP device is patented and marketed today in the whole world.

![Fig.10. SERGI Protection System analysis for different Decompression Set sizes after a lightning surge of 236 kA.](image)

REFERENCES


