SIMPLIFIED INTERNAL ARC-STRUCTURAL SIMULATION

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ABSTRACT

The impact of pressure rise due to an internal arc (IA) event on the structure of a switchgear cubicle is of great importance for a safe design. Switchgear panels are designed for withstanding an internal arc incident as per the testing conditions defined by IEC 62271-200 standard. This paper reports on a calculation procedure employing computational fluid dynamics (CFD) and structural finite element method (S-FEM). The approach is targeting a reduced numerical complexity, straight forward modelling, and stressing as little assumptions as possible. In the proposed method, time varying electric power is used as input along with other parameters for solving mass, momentum and energy equations by CFD. The peak pressure and rise time delivered by transient CFD simulation is needed to perform structural simulation. The structural calculation is performed using dynamic load factor.

INTRODUCTION

The calculation of pressure rise due to an internal arc event employs an analytical approach by evaluating the ideal gas equation together with the first law of thermodynamics. In the simplest case, only the temporal change of pressure inside a closed volume is calculated, assuming thermal equilibrium in each time step and adiabatic outflow condition at the pressure relief [1]. More accurate models consider the temperature dependence of the gas properties up to plasma temperatures of several thousand Kelvin. While this approach is most efficient and often sufficient for the problem given, it lacks of spatial resolution of the spread of the pressure wave. A first approach to get spatial pressure changes was a method that employed differential equations for the pressure wave propagation [2]. Nowadays CFD, employing the finite volume method, has become the tool of choice, as documented in numerous publications, see for example [3] or [4] and references therein.

All these methods rely on assumptions on the heat transferred from the plasma arc to the gas. An effective energy transfer factor k_p is usually employed. This factor is deduced from experiments as a time and volume integrated parameter [1]. The factor k_p depends on the kind of gas, on geometry and also on electrode material and arc current [5]. Strictly speaking, the use of such a parameter is only valid for the panel tested under the imposed testing conditions. This approach remains appropriate only to evaluate the pressure rise caused by a tested panel in a different installation room ,or to a newly designed panel resembling closely to the tested panel. It is not suitable for a completely new panel design. Therefore, a more general approach is desirable for the design of new panels.

A closed solution of the internal arc problem can be addressed by magneto-hydrodynamics, MHD, which seems to work well for small-scale problems [6], and needs tremendous computational effort. In [7] a simpler CFD based scheme was proposed, where a geometric arc model as a cylindrical torch was employed. That approach gave a satisfactory representation of the pressure peak rising in the first couple of 10 ms, without using k_p. At arcing times of 100 ms and longer, though, temperatures increased to high values in the modelled arc region due to a reduced gas density.

METHOD

In the design of new devices for IA event withstand capabilities, the expected peak pressure is of important consideration. It can be obtained by an analytical or CFD approach. To get to an efficient scheme, a sequential coupling of physics with simplifications, similar to what has been proposed earlier by [8], is followed here.. A simulation method is proposed, which does not use the energy transfer factor k_p. Time varying electric power is fed homogeneously to the entire volume of the arcing chamber. Temperature dependent gas properties are used [9], valid up to plasma temperatures of the gas. The radiation losses are approximated using a dynamic net emission coefficient (NEC) approach. The variation of radius of the arc over time and instantaneous current flow among phases are used to estimate heat loss due to radiation. The pressure rise transient obtained is then used to perform a structural analysis of the cubicle. The advantage of this procedure is a direct application of the electric power load to a numerical model with reduced complexity, employing minimum of assumptions, while still achieving a decent match with the experimental results. In general CFD is employed for analysis. For simple closed cubicles, where gas flow and pressure wave spread is not crucial for design evaluation, the scheme can be even more simplified by using the classic analytical method for pressure calculation.

The peak pressure, the rise time, and the initial decay time after the maximum pressure, obtained from transient CFD simulation, is used to perform the structural simulation. Rather than running a full transient non-linear structural simulation, a dynamic load factor (DLF), based on static non-linear structural simulation, is employed. Utilizing linear modal analysis of the structure to obtain the resonant modes, the DLF is calculated from a triangular, piecewise linear approximation of the pressure transient stressing the structure. A static non-linear structural calculation is then performed applying the DLF as a peak-load amplification factor. This yields the deformation and stresses in the structure.

Using this model, internal arc analysis is performed for a typical switchgear.

Computational method

The basic equations describing fluid dynamics are the conservation laws of mass, momentum, and energy. In CFD the solution of this set of equations, the Navier-Stokes equations, are obtained numerically using finite volume method

Mass conservation equation:

The mass conservation or continuity equation is based on the fact that the rate of change of mass inside the fluid element is equal to the net rate of the mass flow into or out of the fluid element across its surfaces.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \vec{v}) = 0 \qquad (1)$$

In equation (1) ρ is the fluid density and v is the velocity vector.

Momentum conservation equation:

Newton's second law states that the rate of change of momentum is equal to the sum of the forces on the fluid. These forces are in general surface forces and body forces. While the surface forces like pressure and viscous forces are normally considered as separate terms in the momentum equation, body forces like gravity and centrifugal forces are in general included in the source term. With this convention the three-dimensional momentum conservation equation reads

$$\frac{\partial (\rho \cdot \vec{v})}{\partial t} + (\rho \cdot \vec{v} \cdot \nabla)\vec{v} = -\nabla p + \nabla \cdot (\eta \cdot \nabla \vec{v}) + S_{Mx} \qquad (2)$$

where η is the dynamic fluid viscosity, p the pressure and S is the source term of force.

Energy conservation equation:

The first law of thermodynamics states that the rate of change of energy of a fluid element is equal to the rate of heat supply plus the rate of work done on the element mainly by surface forces. The energy equation expressed in terms of total specific enthalpy

$$\frac{\partial (\rho \cdot h_0)}{\partial t} + \nabla (\rho \cdot h_0 \cdot \vec{v}) = \nabla (\lambda \cdot \nabla T) + \frac{\partial p}{\partial t} + \nabla ((\tau_{ij}) \cdot \vec{v}) \quad (3)$$

where h_0 is the specific enthalpy, λ is the heat conduction coefficient, T is the temperature, and τ_{ij} is the viscous stress tensor. We use the standard k-ε turbulence model.

The calculation domains are discretized into a mesh of volumes. These domains are the cable, circuit breaker and busbar compartments. At these finite volumes, the above-discussed equations are applied and a solution is obtained by converting them into a system of algebraic equations using mathematical functions as approximation for the variation of dependent variables.

Arc model

Before running the CFD, the power which will heat up the arc-chamber and which will be the source term in the CFD has to be calculated. The electric power generated in an arc is only partly transferred to the gas. The arcing period can be subdivided in subsequent phases. First, with feeding energy to the gas, there is the compression phase, where gas pressure rises. As soon as the pressure relief opens, an expansion phase follows and pressure is decreasing. When pressure becomes as low as the ambient pressure, the emission and thermal phases follow. The periods of interest for analysis are the compression and the expansion phase, The major correction factor for power balance in these periods is radiation. The arc was considered being a cylindrical column with a current dependent radius.

In order to calculate the total magnitude of radiation power losses, the radius of the arc is calculated from Elenbaas-Heller energy balance equation [10].

$$\frac{1}{r} \cdot \frac{d}{dr}\left(\lambda \cdot r \cdot \frac{dT}{dr} \right) + \sigma \cdot E^2 - u = 0 \qquad (4)$$

Here, r is the arc radius, T is the Temperature, and E is the electric field. The temperature dependent parameters are the electric conductivity σ, is the thermal conductivity λ, and the radiation loss density u. To solve (4), E was expressed as function of electric current. The outer region of the arc, where T < 9000 K, is almost transparent above wavelengths of 250 nm [10], below there is a strong absorption. With increasing arc temperature the radius decreases, so effectively the net radiation losses do not vary much. This can be used to fix temperature at 11000 K. Then the radius of the arc can be approximated by function of current, shown in Figure (1).

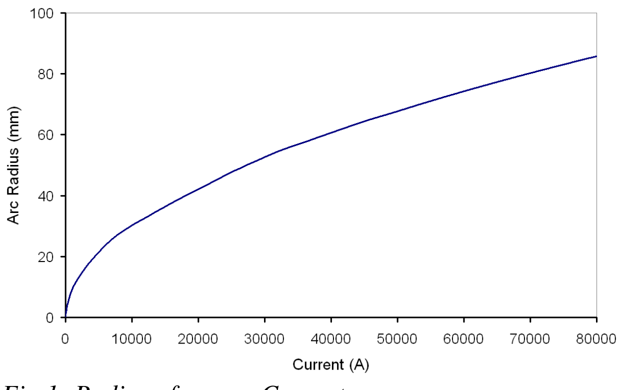

Fig.1: Radius of arc vs. Current

The length of the arc is approximated by the physical distance between the phases where the arc will burn. Figure (2) shows the current between each of planar aligned busbars in a three-phase arc event from measurement.

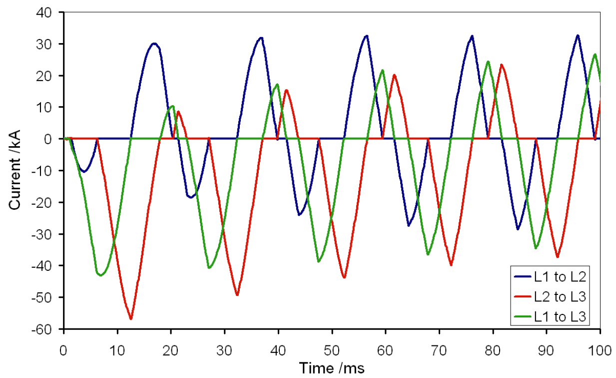

Fig.2: Current flow during internal arc between phases (3 phase arc test example)

Eventually we have all information to calculate radiation losses as a function of current. The radiation energy is subtracted from the fed electrical energy. Figure (3) shows an example of a resulting power calculation.

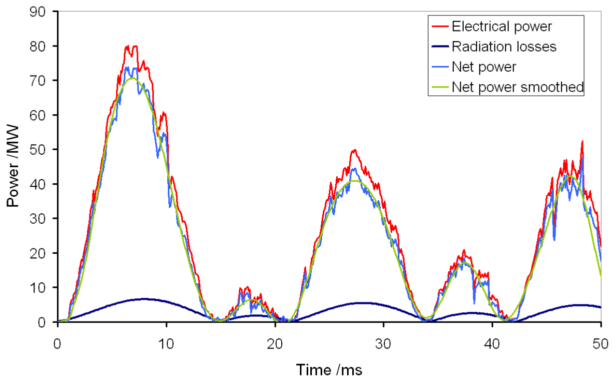

Fig.3: Electrical energy, Radiation energy, Net energy as a function of time

Structural mechanics

The calculation of mechanical stresses of the device structure under the dynamic pressure load can be greatly simplified by using a dynamic load factor. The pressure pulse obtained from CFD calculation can be approximated by a triangular pulse shape. A modal FEM analysis delivers the natural frequencies of a given structure. The response of the structure to the pressure pulse can then be calculated in a static structural FEM simulation applying the equivalent static force, which is determined by the dynamic load factor.

The response of an undamped single degree of freedom system with an arbitrary load is given by Duhamel's integral [11]:

$$y(t) = \frac{1}{m\omega}\int_0^t F(\tau)\sin\omega(t-\tau)d\tau\,, \qquad (5)$$

Where ω is the natural frequency of the structure. The dynamic load factor (DLF) is defined by

$$DLF = \frac{\max(y(t))}{\max(y_{stat}(t))} \qquad (6)$$

Results and comparison with experiments

As an example for the procedure proposed here, the method was implemented in the design of a GIS. The focus had been on the test of the cable compartment at 31.5 kA (r.m.s.). As can be seen from Figure (4), the pressure rise calculated for the cable compartment matches closely with the measurement at the cable door. The initial pressure peak in measurement is enhanced due to reflection of the impacting pressure wave shortly before the overall pressure in the compartment becomes maximum. In calculations where the energy is homogenously fed to all volume of the compartment, this feature can not be resolved. At the same time the pressure relief at the rear of the compartment opens, reducing the overall pressure rise in the compartment.

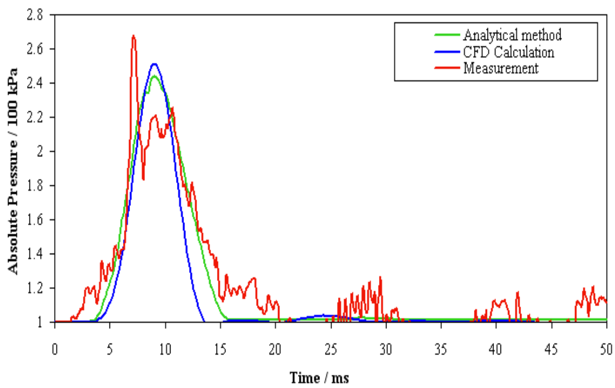

Fig.4: Absolute Pressure vs. Time in cable compartment

Implementing the structural part of the method, the pressure rise transient is approximated as triangular pulse. The modal frequency of the structure is calculated and used in calculating the DLF. Figure (5) shows the static and the dynamic response of a structure to a triangular pulse. From the ratio of both maxima the DLF is calculated according to equation (6). The traces resemble the response of the cable-door for the given excitation as a function of time. The static response resembles directly the triangular load, since we have to consider a static response direct proportional to the load. The fundamental eigenfrequency of the door is as low as 19 Hz. Thus the structure cannot follow the load instantaneously and bulging of the door is according to an equivalent static load of 86% of the maximum pressure. For the hinges, resembling a rigid fixation, have to withstand the full pressure load.

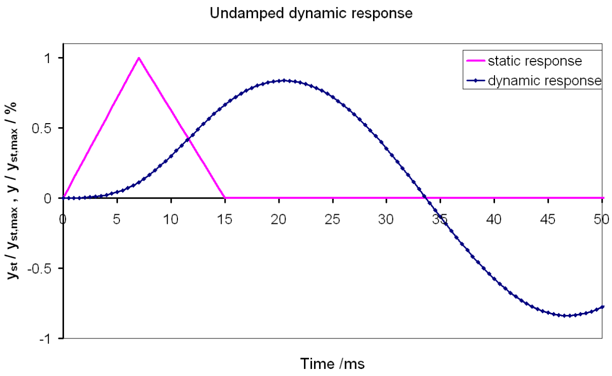

Fig 5: Undamped dynamic deflection of a structural element with 19 Hz Eigenfrequency subject to a short pressure pulse as compared to a pure static response

Using the DLF, we performed a non-linear static structural calculation to get the maximum deformations and stresses. As indicated by the mechanical stresses obtained by simulation, also in reality the door could withstand the arc event without rupture. The maximum total structural deformation was predicted as shown in Figure (6). The component of plastic deformation was in agreement with the permanent deformation resulting from the test.

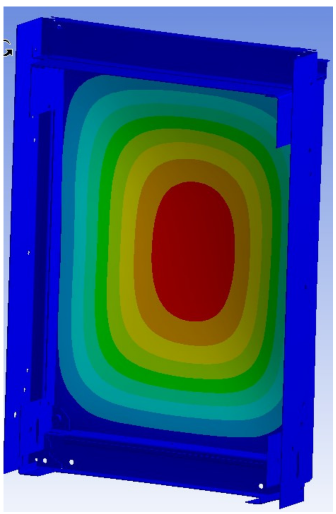

Fig.6: Deformation on the Cable compartment door

CONCLUSIONS

We have shown a method of evaluating the effect of internal arc on switchgear cubicles, which simplifies the calculation but also does without fit parameters. From first principles and parameters applicable to testing, we find reasonable agreement between calculation and tests performed.

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