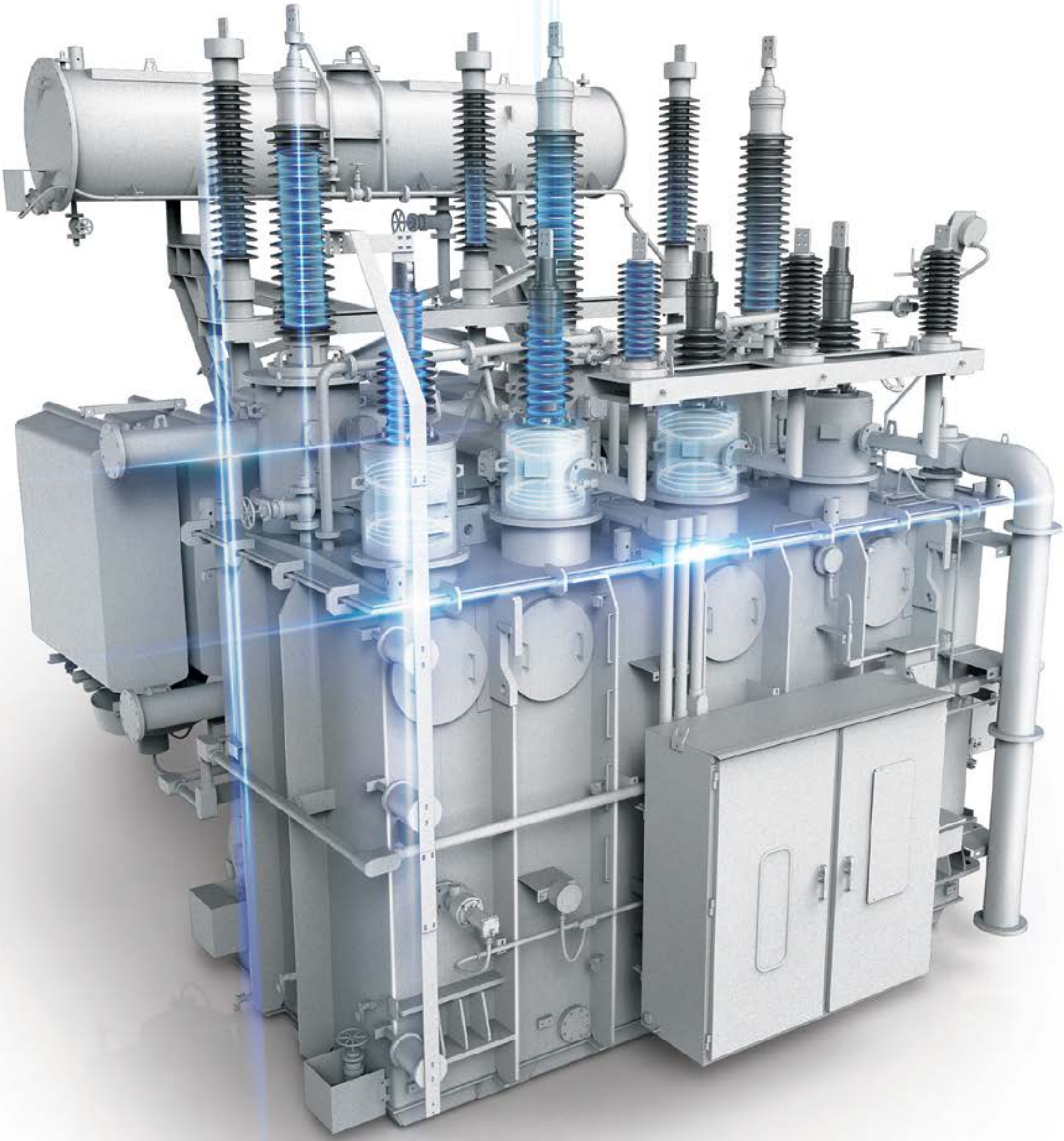

ABSTRACT

In general, a transformer is designed and manufactured to operate under normal conditions. However, unexpected fault events occur due to various reasons in real-life substations. When such events do occur, an electric arc inside a transformer vaporizes the insulating oil, leading to a generation of very high expansion pressure. Once this pressure exceeds the designed threshold, the tank is then compromised, and oil starts to leak, becoming a potential cause of fire or explosion.

DPRS (Dynamic Pressure Resistant System) transformer has been developed to cope with such unexpected events. In general, a PRD (Pressure Relief Device) is installed on a transformer to stabilize the pressure inside the tank. However, it requires a certain amount of time for this device to operate. DPRS transformer is designed to withstand the immediate pressure increase without severely damaging the tank (severe enough to cause an oil leak) until the PRD starts operating. Although not as much as to cause a leak, the tank will still be deformed as a result of the pressure increase. Then, insulating oil expanded by the arc is emitted safely through a designated path as the PRD starts to operate. DPRS transformer does not require additional equipment to prevent damage to the tank and is also capable of preventing fire while maintaining a similar configuration to common transformers. Due to these merits, the global demand for DPRS transformers is steadily increasing.

In this article, the DPRS transformer tank design procedure and tank deformation prediction technology are presented. Additionally, a brief introduction to the explosion-proof performance verification test is addressed.

KEYWORDS:

arc explosion; pressure behaviour; dynamic analysis; explosion-proof test

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An internal electric arc may occur due to deterioration or unexpected fault events and disturbances, and it vaporizes insulating oil and generates an immediate pressure increase inside a transformer

DPRS transformer

Dynamic pressure resistant system - Part I

DPRS transformer (dynamic pressure resistant system)

An electric arc occurring inside a transformer may cause vaporization of insulating oil, generating a pressure level that is capable of damaging the tank in a very short period of time. In this article, a transformer tank design technology that allows a safe emission of insulating oil through a designated path without damaging the transformer tank during unexpected arcing events is presented.

1. Introduction

Rarely does a transformer experience a sudden internal pressure increase driven by electric arcs, as it is designed and manufactured with proper insulation considerations. However, an internal electric arc may occur due to deterioration or unexpected fault events and disturbances. This arc vaporizes insulating oil and generates an immediate pressure increase inside a transformer. If the pressure increase time is shorter than the response time of the PRD, the transformer tank has to fully absorb the pressure. In general, such abnormal pressure is ~5–6 times as high as the allowable pressure threshold, leading to severe damage. Once the tank is compromised, insulating oil leaks sporadically and becomes a potential cause of environmental contamination, explosion, etc.

DPRS transformer has been developed with the purpose of minimizing such risk and responding to the ESG (Environmental, Social and Governance) policies. It is designed to withstand the immediate pressure increase generated by the internal arc until the PRD starts to operate. As soon as the PRD starts its operation, the insulating oil is emitted through PRD, and the internal pressure is stabilized. Since the emitted oil is transported safely through a designated path, there is a low risk of contamination by oil leakage or fire. DPRS transformer does not require additional equipment to prevent damage on the tank and is also capable of preventing fire while maintaining a similar configuration to common transformers. Due to these merits, the global demand for DPRS transformers is steadily increasing.

This article introduces the design technology utilized in the DPRS transformer development and its verification tests.

More specifically, non-linear static and dynamic analyses for tank deformation prediction are presented. Additionally, a verification test using an actual 500 kV DPRS transformer to demonstrate the accuracy of this method is addressed.

Figure 1. DPRS transformer

Designing a DPRS transformer requires accurate prediction technologies on the tank deformation and internal pressure behaviour, which is usually performed through FEM

2. Tank design process

Designing a DPRS transformer requires accurate prediction technologies on the tank deformation and internal pressure behaviour. Generally, the design verification is performed through FEM non-linear static analysis and non-linear dynamic analysis.

Firstly, non-linear static analysis is performed based on the material's non-linear characteristics and internal pressure calculation based on IEEE C57.156 [1] and CIGRE 537 [2]. This approach allows a structural evaluation of the design in a short period of time compared to non-linear dynamic analysis. However, it usually leads to a conservative evaluation since it involves the assumption of the calculated pressure being uniformly applied to the entire tank interior. As a result, the transformer tank generally ends up being overdesigned with a high safety factor.

The other approach is the non-linear dynamic analysis. This approach requires a dynamic analysis of the internal pressure increase driven by the arc energy with considerations of the fluidic characteristics of insulating oil. Based on the CIGRE 537 [2], fluid-structure interaction (FSI) analysis is performed. This approach leads to a more accurate evaluation compared to non-linear static analysis since it reflects the variables, including the location of the arc, the magnitude of the arc energy and geometric characteristics of the main body structure. However, this requires a longer computation time.

2.1 Analysis process

The design of a DPRS transformer follows the steps shown in Fig. 2 while complying with the customer requirements. Firstly, arc energy is calculated per IEEE C57.156 [1] with arc current, arc voltage and arc duration. Then, the designer selects the more appropriate method between non-linear dynamic analysis and non-linear static analysis.

The non-linear dynamic analysis approach requires a determination of potential arc locations. With the designer's engineering insight and evaluation, these potential arc locations are determined as a first step. Then, FSI* analysis is performed with considerations on arc energy, tank and insulating oil.

The non-linear static analysis approach requires a calculation of flexibility** of the

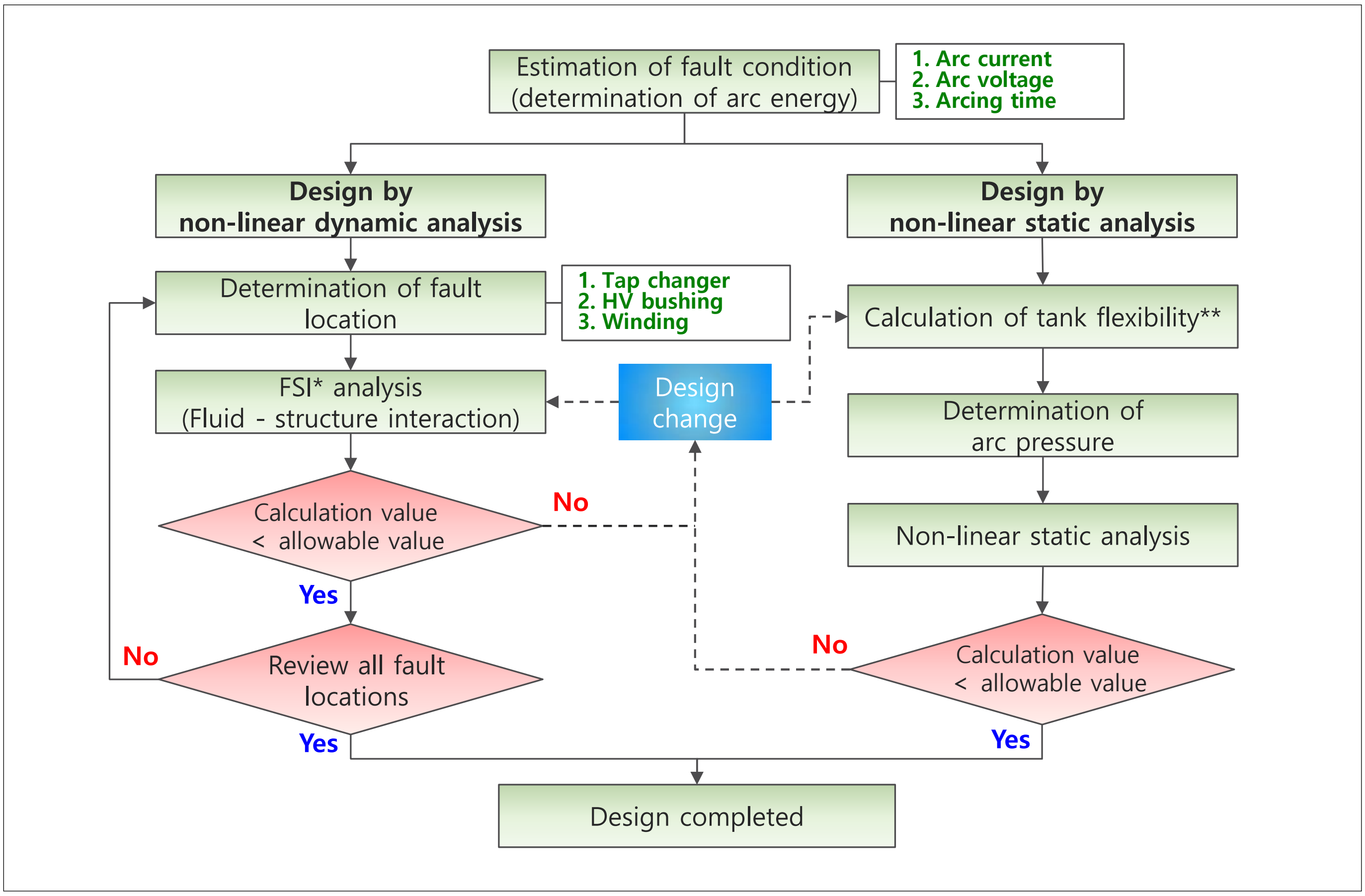

Figure 2. Tank design process

*FSI (Fluid-Structure Interaction): Non-linear dynamic analysis with considerations on the interaction between fluid dynamics and structure

**Flexibility: Design variable that represents the structural characteristics of a tank versus the pressure increase inside a transformer tank versus the pressure increase through repetitive analyses. Then, using the calculated flexibility data and arc energy, tank pressure (P_s) is calculated. If the allowable pressure of the designed tank does not meet this tank pressure (P_s), the designer revises the tank design and iterates the process from the flexibility calculation.

The dynamic and static analyses each have a different purpose. Depending on this purpose, the designer selects a method from the two options. In general, non-linear static analysis is used for the design verification of the DPRS transformer tank. On the other hand, non-linear dynamic analysis is generally used for estimating the arc location for root cause analysis of a failure, understanding the internal pressure transfer characteristics for test condition definition and verifying the tank design. Despite the fact that the non-linear dynamic approach leads to a more accurate evaluation and helps avoid over-engineering, it requires a very long computational time. Hence, using the static analysis approach is more common, which requires less computation time and leads to a more safe and more conservative design. Through a statistical analysis of the transformers in the past, it is known that an arc usually occurs near the tap changer, HV bushings and windings. This is mentioned in Section 3.1.1 of CIGRE 537. It should be noted that 3D solid analysis FEM is the standard process.

In order to calculate tank pressure value, arc energy needs to be calculated first with the arc voltage, arc current and arc duration defined in the specifications by the customer

2.2 Non-linear static analysis

The tank pressure of a DPRS transformer is calculated per IEEE C57.156 [1] and CIGRE 537 [2]. In order to calculate this value, arc energy needs to be calculated first with the arc voltage, arc current and arc duration defined in the specifications by the customer. This arc energy defines the design load (internal tank pressure or explosive energy) in either a static or dynamic analysis. In general, abnormal current conditions that are expected to occur at a substation level are defined in the customer specifications. However, there are occasional cases where the transformer manufacturer proposes the arc voltage, for this value is dependent on the insulation design of a transformer.

As stated above, the internal pressure used in the non-linear static analysis is calculated per Section 4.3 of CIGRE 537. This equation includes arc energy, flexibility and factors that reflect the dynamic characteristics. Firstly, arc energy is defined by the fault current duration and arc voltage level. This calculated arc energy becomes an important parameter that defines the internal pressure in non-linear static analysis. An actual arc explosion exhibits a dynamic behaviour. In order to reflect the impact of this behaviour, conservative factors are applied in the equation. Also, the tank flexibility and insulating oil characteristics are considered to determine the final tank pressure.

Results of non-linear static analysis are impacted by the non-linear characteristics of a material, and this non-linearity shows a difference per its geometric shape. Hence, it is crucial to apply accurate material properties with consideration of the material itself and its geometric shapes being used in the DPRS transformer. Metals start showing plastic deformation once the stress exceeds the yield stress. At this point, the metal begins to have non-linear stress-strain characteristics, and this curve can be measured and recorded by test. The test on the material properties measurement will be introduced in detail in chapter 3.

Using the calculated tank pressure and accurate material properties, the designer evaluates the structural safety of the DPRS transformer.

Arc energy E (Joule, J) is then a function of arc current I arc (Amperes, A), voltage V arc (Volt, V) and duration t arc (seconds, sec), as shown in the following equation (1).

$$E = \int_0^{t_{arc}} V_{arc}(t)\, I_{arc}(t)\, dt \qquad (1)$$

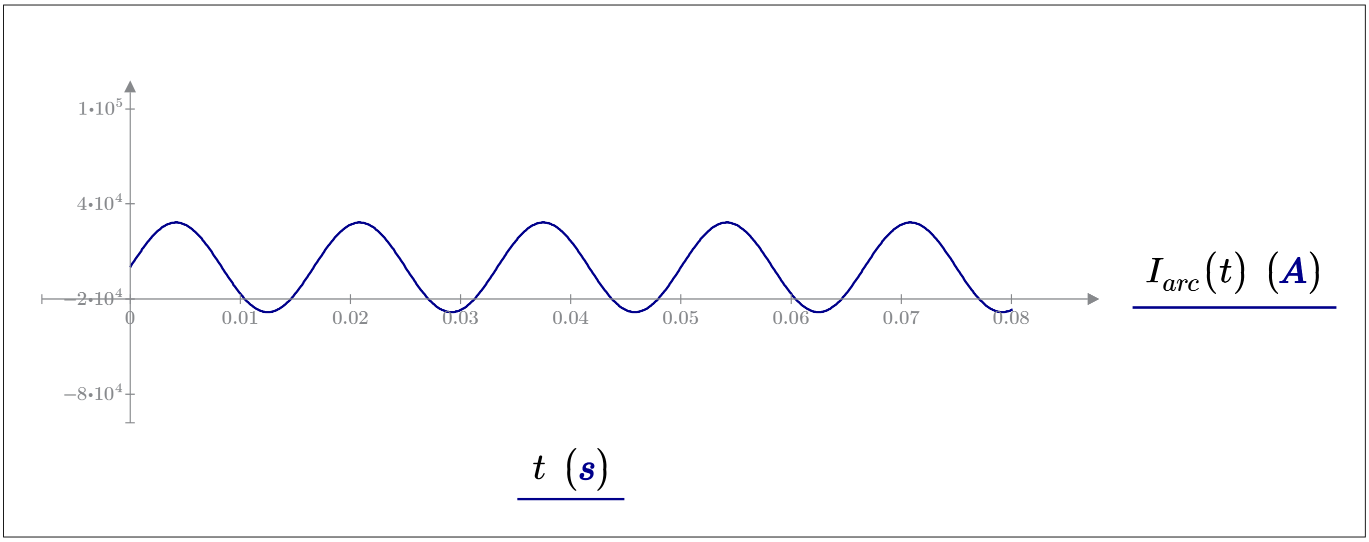

Figure 3. Typical waveform of arc current

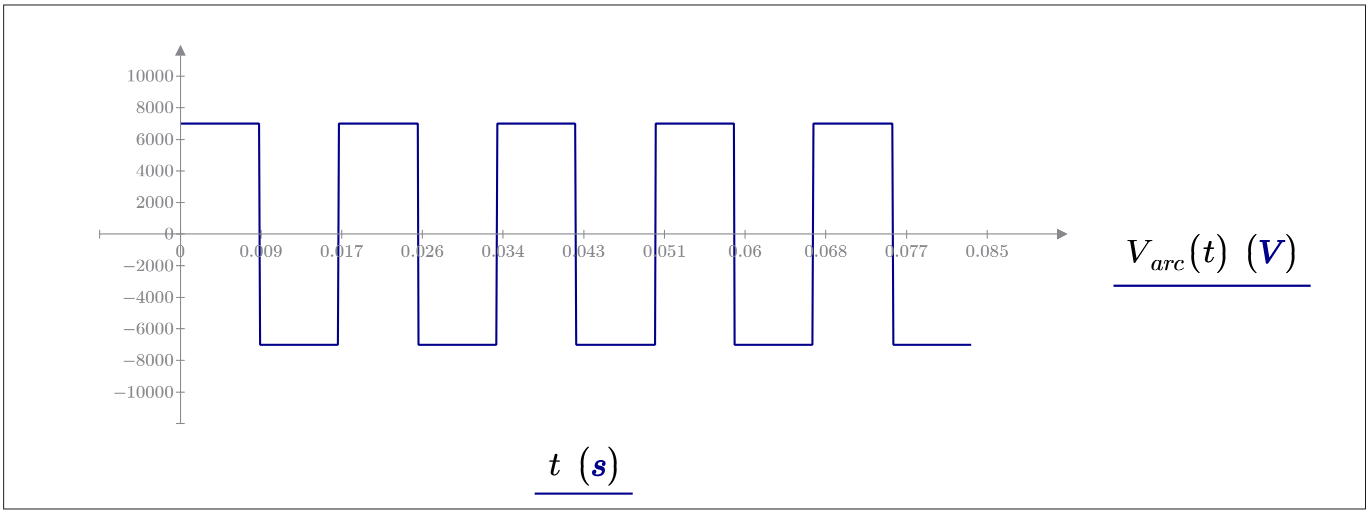

Figure 4. Typical waveform of arc voltage

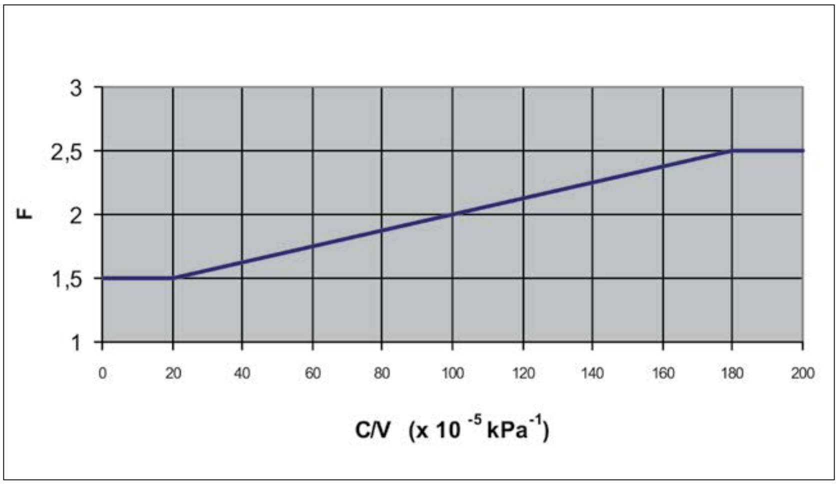

Figure 5. Variation of the dynamic amplification factor F for Equation (2)

Using the calculated tank pressure and accurate material properties, the designer evaluates the structural safety of the DPRS transformer

Table 1. Calculation example of determining tank pressure

ITEM		DPRS transformer (under 500 kV)
Arc voltage	Value	7 kV
Arc current	Value	20 kA
Arcing time	Value	5 cycles (≈ 83msec)
Arc energy [E]	Equation	$\int_0^t VI(t)dt$
	Value	10.5 MJ
Dynamic factor [F]	Value	1.5
Tank flexibility [C]	Value	0.0091 m³/kPa
Internal tank pressure (arc pressure) [Pt]	Equation	$F\left[100\sqrt{\frac{1}{4}+\frac{kE}{100C}}-50\right]$
	Value	291.0 kPa

The Equation (2) shows the tank pressure, where:

Ps is the calculated tank pressure in kPa above atmospheric; E is the fault(arc) energy level in kJ; k is the arc energy conversion factor (= 5.8×10^{-4} m³/kJ)) [@2000 K]; C is the tank expansion coefficient (m³/kPa); F is the dynamic amplification factor given in Fig. 3; V is the volume of oil in the main tank (m³).

$$P_s = F\left[100\sqrt{\frac{1}{4}+\frac{kE}{100C}}-50\right] \qquad (2)$$

A calculation example of determining tank pressure is shown in Table 1.

A statistical analysis of the transformers in the past shows that an arc usually occurs near the tap changer, HV bushings and windings

2.3 Non-linear dynamic analysis (FSI analysis)

Considering the transformer specifications, lead arrangement and components, the designer determines the locations where the arc could potentially occur. A statistical analysis of the transformers in the past shows that an arc usually occurs near the tap changer, HV bushings and windings. This is mentioned in Section 3.1.1 of CIGRE 537. These locations have relatively shorter insulation distances and are near high voltage or current. Along with such general knowledge, the manufacturer's engineering insight and experience help the designer determine these locations more accurately.

The analysis is performed using verified material properties and the FEM technique. For the material properties, the Johnson-Cook model [3] obtained with considerations of the geometric shape, parent metal, and weld zone has been applied. These properties have been verified by test as they were in the static analysis approach. The analysis is performed using the commercial FEM program ANSYS which is an appropriate tool for predicting the dynamic behaviour of the tank, reflecting the interaction between solid and fluid. Setting the conditions as close as possible to an actual arc occurrence inside a transformer, FSI analysis is performed. This method has been proven to show similar results to the actual test, which will be explained in chapter 4. Despite its long computation time, the non-linear dynamic analysis approach allows the designer to obtain and understand the structural characteristics (pressure transfer behaviour, stress, deformation, etc.) over time, while the static analysis approach does not.

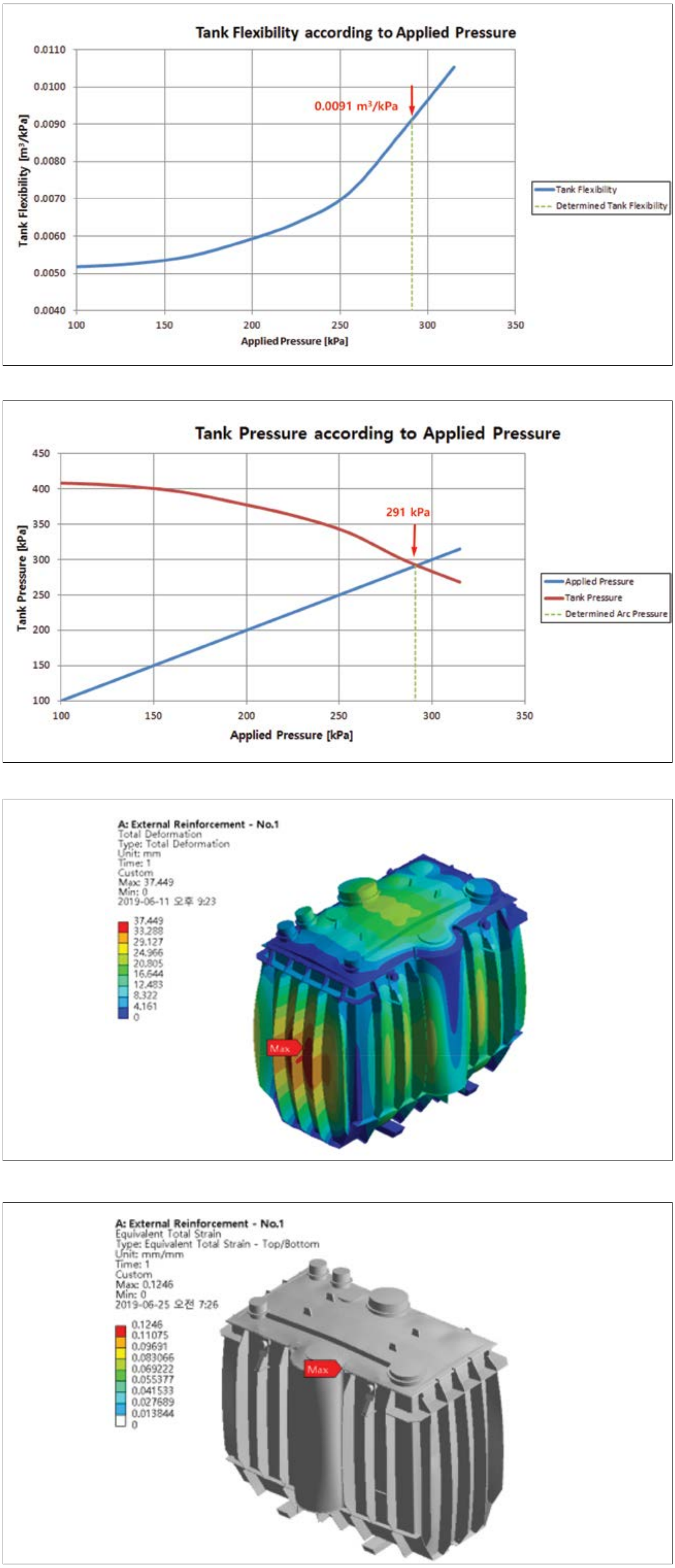

Figure 6. Non-linear static analysis

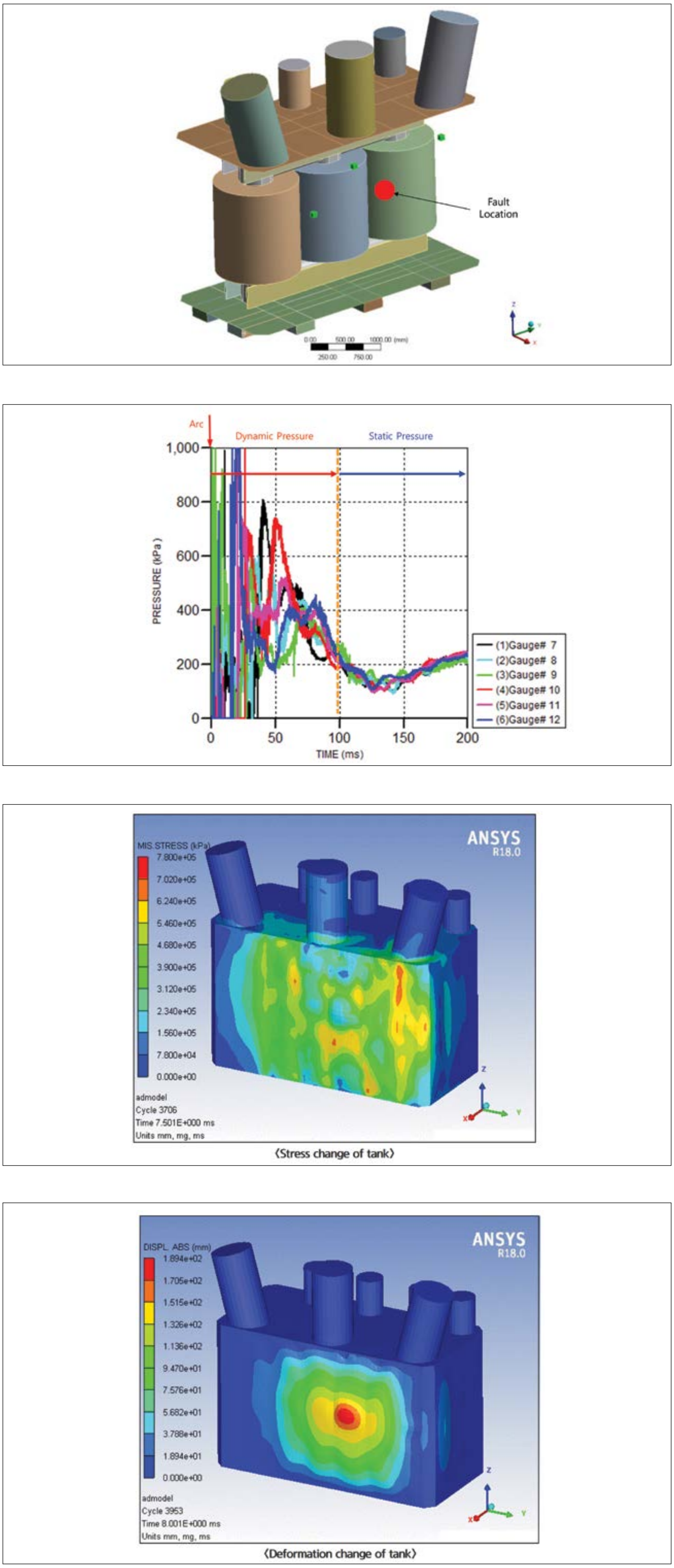

Figure 7. Non-linear dynamic analysis

PEER REVIEWED

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