Prevention of Tank Rupture of Faulted Power Transformers by Generator Circuit Breakers

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Abstract

Internal fault arcs in power step-up transformers occasionally occur at different locations inside the tank. In this study it has been investigated to what extent generator circuit breakers (GCB) between generator and transformer may prevent explosion or severe damage due to pressure rise caused by the fault arc. Using sources from literature, study of fault cases that occurred in the past, and research of arc-current and arc-voltage conditions, a procedure was established to check the probability to what extent a GCB may reduce severe transformer damage and increase safety by prevention of fire. Following this procedure some actual fault-case studies show that GCB are effective in saving the transformer tank with a probability up to more than 80 %. Comparison with failure data verify the calculations.

1 Introduction

Step-up transformers in power plants normally show high availability. However, in rare cases internal dielectric flash-overs occur resulting into a fault arc inside the transformer causing significant internal pressure rise by production of large quantities of gas (mainly hydrogen) due to dissociation of the oil. The amount of gas produced has been investigated in the past by several investigators [1–5] with somewhat diverging results. Depending on the fault-arc energy, (which is a function of current value, arc length and arc duration [1–3]), the pressure rise usually is sufficiently high to crack the transformer tank or to blow out one or more of the bushings. In most cases severe damage occurs inside the transformer, but also other equipment of the plant installation is jeopardized by burning oil or hydrogen outside the transformer. Unacceptable outage of the plant or at least parts of it normally is the consequence.

The current of the fault arc is delivered both by the system from the high-voltage side and by the generator. Its value is determined by parameters as short-circuit impedance of transformer, generator and network and the number of short-circuited windings as well.

The current fed by the system is interrupted by the circuit breaker installed at the high-voltage side. The minimum interrupting time for two cycle breakers is about 40 ms. The generator continues to deliver a significant portion of the fault-arc current until it is de-excited (within seconds). Therefore the tank pressure rises steadily also after separation of the high-voltage system and even if the current fed by the generator is comparably lower than the portion delivered by the system, de-excitation normally comes too late to save the transformer.

Today it becomes more and more common to install a generator circuit breaker (GCB) between generator and step-up transformer for operational and safety reasons as well. In this context the question arises whether serious internal or external damage can be prevented if the generator-fed fault current is interrupted by a GCB quickly enough.

In order to answer this question a calculation procedure has been developed by means of a suitable computer code. The goal was to estimate the probability to what extent installation of a GCB is preventive for tank rupture in case of an internal fault. As a basic input for the calculations the following quantities had to be investigated:

Value of Fault-Arc Energy

- Calculation of fault-arc current (which is rather complex in case of only part of the winding is short circuited).
- Estimation of the arc voltage which depends on the arc length and thus on the location of the fault.
- Calculation of arc duration determined by the protection system, i. e. switching moments of the GCB and the high-voltage breaker.

Pressure Rise Inside the Tank as a Function of Arc Energy

Results presented in literature [2, 6] have been analysed. [6] presents a theory for small distribution transformers where in general the vessel was assumed to be stiff. Where in [6] the first pressure peak a couple of milliseconds after fault initiation was of main interest, for our study a static approach seemed to be more appropriate since the purpose was to investigate an average pressure rise over a longer period of time (up to some seconds). Therefore the formula introduced in [2], which also takes into account the expanding potential of the tank, seemed to be a suitable bases.

Study of the Behaviour of a Transformer Vessel Exposed to Inside Pressure

Not much data are published on the cracking behaviour of transformer tanks when pressurised. Several relevant transformer manufacturers in Europe have been consulted to obtain more insight.

Statistical Fault Behaviour of HV Transformer

In order to learn from field experience, 25 failure cases have been analysed as good as failure data have been recorded. Source of information of this part of the study were a well-known insurance company and several transformer manufacturers and utilities as well. For those cases where sufficient data have been recorded during the fault, the calculation procedure was applied and the calculated results were compared with the real event.

2 Strategy of the Calculation Procedure

The flow chart of the calculation procedure is shown in **Fig. 1**.

3 Determination of the Essential Quantities

3.1 Energy of the Fault Arc

3.1.1 Fault Location

The arc energy is primarily a function of arc duration, arc current and arc voltage. The later two strongly depend an the location of the fault, i. e. the location influences the short-circuit impedance and the arc length influences the arc voltage. Therefore different fault locations have been categorized as listed below and their probability of occurrence estimated by analysis of 25 failure cases.

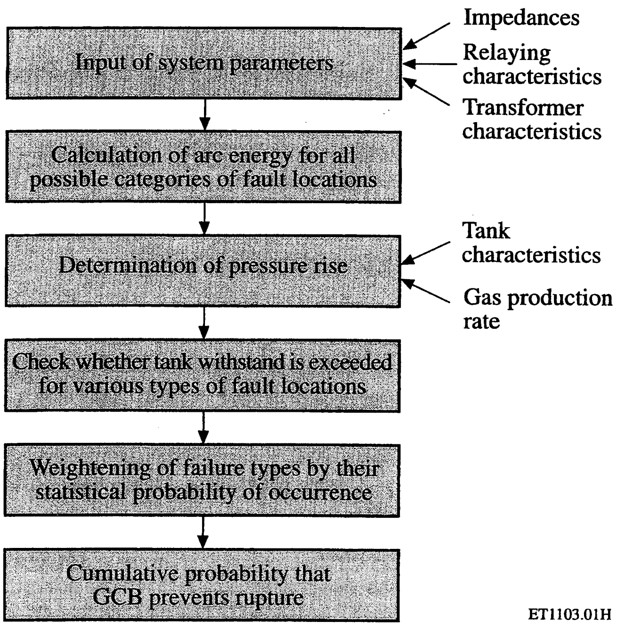

Fig. 1. Principle flow chart of the calculation procedure (GCB Generator Circuit Breaker)

The failure data have been provided by an insurance company and GCB manufacturers and utilities. Transformers in the range of 1,7 MVA to 1 500 MVA have been analyzed. Often there was not a complete failure data set available and estimations were necessary. The numbers in brackets indicate the estimated probability for a certain failure location inside the tank derived from the available data:

- Flash-over from high-voltage (HV) conductor to ground (10 %).
- Flash-over from low-voltage (LV) conductor to ground (5 %).
- Flash-over across the bushing with pressure build-up in the tank (15 %).
- Flash-over across the bushing, with bushing is blown out (15 %).
- Partial shorting across several turns:
  - arc along the turns (15 %);
  - arc from winding to tank (15 %).
- Shorting across two positions of the tap changer (25 %).

3.1.2 Calculation of Arc Current

Significant effort had to be taken to determine the arc-current value. **Fig. 2** shows in principle the current value depending on the moments of interruption t_1 and t_2 of the breakers at the high-voltage side and of the GCB, respectively.

During the first interval T_1 the arc is fed by system and generator ($I_{\mathrm{arc}} = I_{\mathrm{net}} + I_{\mathrm{gen}}$). After disconnection of the system at t_1 during the second interval T_2 the arc is only fed by the generator until disconnection by the GCB. In case there is no GCB, the generator continues to feed the arc during a third time interval T_3 with a slow current decay by de-excitation within seconds.

For the arc-current value two major groups of arc locations are relevant, which have to be handled differently for calculation:

- short circuit of a complete transformer coil,
- short circuit of a portion of a coil.

If the arc shorts a complete coil, the value of the arc current is approximately the same as if the short circuit would occur directly at the transformer terminals. It can

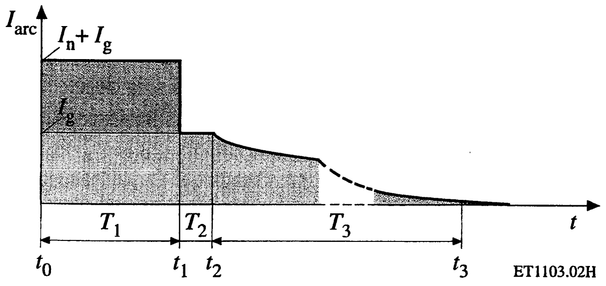

Fig. 2. Arc current I_{arc} depending on fault time (I_g generator current; I_n net current)

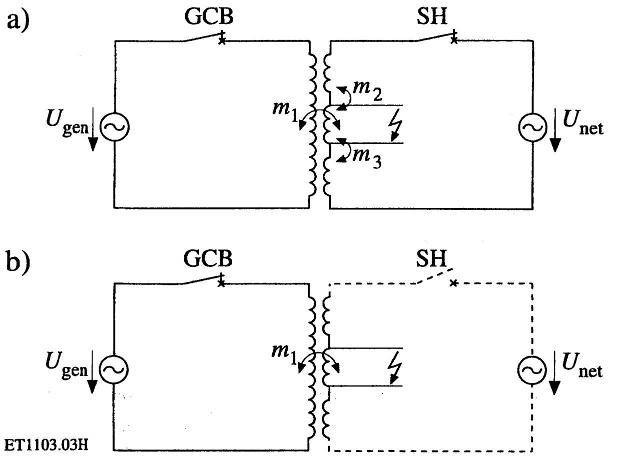

Fig. 3. Shorting across part of the winding, HV side (GCB Generator Circuit Breaker; SH Switch at the HV side)
a) Current fed by generator and system
b) Current fed by generator only

be calculated by means of network impedances and the rated short-circuit impedance of the transformer, which is state of the art.

If only a portion of the HV coil is bridged by the arc, conditions become significantly more complicated. The coil is split into two parts, i. e. the short-circuited part and the remaining (non shorted) part (**Fig. 3**).

Apart from the impedances in the HV and LV system, the arc current is influenced by three additional parameters:

- magnetic coupling m_1 between the LV coil and the shorted turns (Fig. 3a),
- magnetic coupling m_2 and m_3 between the non shorted turns and the shorted turns of the HV coil (Fig. 3a).

The values of these coupling factors m_1, m_2, m_3, strongly depend on the geometrical conditions (length and position) of the short-circuited portion of the coil.

I. Coupling factor m_1:

For calculation of the coupling factor m_1 between the LV winding and the shorted turns of the HV winding (according to Fig. 3b) the following considerations apply:

Two coaxial coils have maximum magnetic coupling m_1 if their geometrical heights are equal and there is no displacement h against each other in axial direction (**Fig. 4**). If one coil is of smaller length b, the coupling is reduced (assuming that the number of windings does not vary). Also displacement by a certain value of h causes further reduction of m_1.

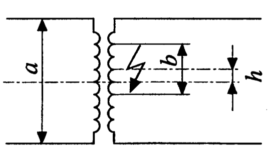

Fig. 4. Position of the shorted windings

Fig. 5 shows how m_1 depends on the length b if the shorted part varies in size with the axial displacement h as a parameter. The smaller b and the higher h, the smaller is m_1.

The curves given in Fig. 5 have been calculated applying a mathematical analytical method, which was originally used to determine the current in induction furnaces [7].

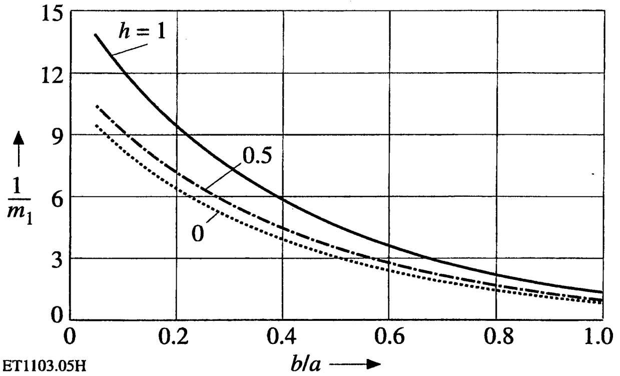

Fig. 5. Dependence of $1/m_1$ on the length of shorted turns with h as a parameter

For comparison the curves in Fig. 5 have also been calculated for a 85 MVA transformer by means of numerical simulation employing a computer code of a transformer manufacturer (unpublished). The results for m_1 obtained by the two different methods match sufficiently, which verifies both ways of calculation.

II. Arc current fed by the generator only (within T_2, T_3):

In case of shorting a portion of a coil by the arc, the number of shorted turns is assumed to be proportional to the geometrical length of the shorted part of the coil.

Thus the arc current is determined by m_1 and by b/a as well. According to the conversion of the current from the primary (feeding winding) to the secondary winding (shorted part) – the fewer turns are shorted, the higher the current will be and the arc current I_{arc} can be approximated by:

$$I_{arc} = I_{rs}\,(a/b)\,m_1(h) \qquad (1)$$

with

I_{arc}	arc current,
I_{rs}	short-circuit current for flash-over at HV terminal,
b/a	amount of shorted turns in reference to the amount of turns of the entire coil,
m_1	coupling factor of short circuited transformer.

Fig. 6 shows the arc-current value over the percentage of shorted turns. The arc current is normalized by the short-circuit current of an intact transformer with HV terminal fault.

The curve shows a minimum at about 30 % because of two contrary effects. On the one hand the current is lower for smaller geometrical length of the shorted turns because of the smaller magnetic coupling. On the other hand the current is larger with decreasing amount of turns being shorted because of the changing conversion ratio from primary to secondary side.

III. Arc-current fed by generator and system (within T_1):

For the time interval T_1, where both sources feed the arc, coupling factors m_2 and m_3 become relevant too. Assuming the value of the current being fed by the generator does not change after disconnection of the HV line, an approximation for the current value during T_1 can be found by the following considerations:

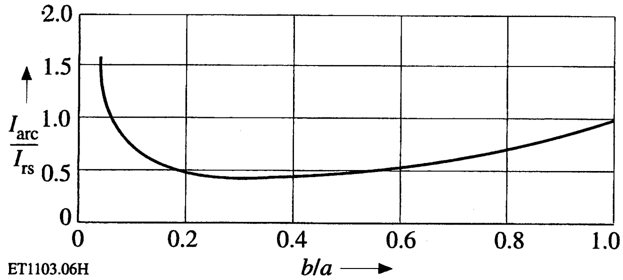

Fig. 6. Arc current depending on the amount of shorted turns (I_{arc} arc current; I_{rs} short-circuit current for the intact transformer)

The portion of the failure current being delivered by the generator is set into relation with the value of the current being fed by the system in case of a terminal fault. This is done for a fault on the HV terminal as well as on the LV terminal. For an internal fault the average of these two values is taken. Knowing the arc current after disconnection of the HV side and the ratio of the generator current to the current fed by the system, the current for the time interval T_1 can be calculated.

Partial short circuit on the LV side was not considered in detail because the probability of this type of fault is very small.

3.1.3 Arc Voltage

Besides the arc current, the arc voltage is an essential parameter for the arc power and thus the arc energy. From literature it is known that the arc voltage is approximately proportional to the arc length [2]. A gradient of 50 V/cm ... 100 V/cm is given, depending on how much the arc column is quenched. Newest research has shown that also hydrostatic pressure influences the arc voltage [6], however, this phenomenon has been considered as a secondary effect for our approach as the arc length is the more influencing parameter which scatters already widely in reality.

In our calculations 100 V/cm have been applied to be on the conservative side in regard to pressure rise. To calculate the arc length the different types of possible arcing faults are considered (see chapter 3.1) and appropriate lengths and the according arc voltages are estimated.

For higher rated voltage, higher length has to be considered (In our calculations 30 cm ... 40 cm coil to tank and 200 cm ... 260 cm across the coil have been applied as average values).

3.1.4 Arc Duration

To obtain the arc duration, the specific conditions in a power plant have to be studied for each case. The duration of the arc burning is usually known by the relaying time and the switching time of the breakers and/or the de-excitation time of the generator.

3.2 Calculation of Pressure Rise

For calculation of the pressure rise inside the tank the volume of the (compressed) gas produced by the arc is set equal to the expanding volume of the tank. The corresponding eq. (2) was taken from [2]:

$$A\,p(t) = C\,U\,I\,t \tag{2}$$

with

p pressure (in Pa),
C gas-production rate (in m^3/J),
U arc voltage (in V),
I arc current (in A),
t time of the arc burning (in s),
A tank expansion coefficient (in m^3/Pa).

The left side of the equation expresses the increase of tank volume by pressure, while A is a tank expansion coefficient (see below). The right side of eq. (2) gives the amount of produced gas depending on the arc energy UIt and a gas production coefficient C. Approximated that C is a linear function of the pressure $p(t)$ (derived from the ideal gas equation), i. e.

$$C = \frac{C_0}{1 + p(t)/p_0} \tag{3}$$

with

p_0 normal air pressure (in Pa),
C_0 gas production rate at p_0 (in m^3/J),

eq. (2) turns into:

$$p(t) = \sqrt{\frac{1}{4}p_0^2 + \frac{C_0 I U t}{A}p_0} - \frac{1}{2}p_0\,. \tag{4}$$

This is in consistency with [2] where p_0 was set to be of the value 0.1 MPa or 1 bar, respectively.

3.2.1 Gas Production Rate C_0

For coefficient C_0 values have been published between $50 \cdot 10^{-9}\ m^3/J$ and $500 \cdot 10^{-9}\ m^3/J$ [1–3,5,7]. It seems that $200 \cdot 10^{-9}\ m^3/J$ matches best with the majority of published data. Thus this value has been applied for our calculations.

3.2.2 Tank Characteristics

The tank expansion coefficient A indicates the amount of tank deformation when pressurized. It expresses the amount of increase of tank volume in m^3/Pa (e. g. some manufacturers specify $3 \cdot 10^{-6}\ m^3/Pa$ ... $7 \cdot 10^{-6}\ m^3/Pa$ [2]).

As a guideline given by a big transformer manufacturer it is stated that the admissible wall distortion in the centre can be up to 0.7 % when 0.1 MPa overpressure is applied. From this value, A can be estimated in case the tank dimensions are known. For a first approach in our study, the tank was represented by a rectangular box with six flat walls. The volume increase was then approximated by a rising pyramid on top of each wall.

Most uncertainty is given for the real withstand pressure of the tank before cracking. Transformer manufacturers specify at least 0.1 MPa overpressure, but not an exact value (which seems to be impossible, at least in a general way). As a plausible approach 0.12 MPa to 0.15 MPa withstand pressure was assumed.

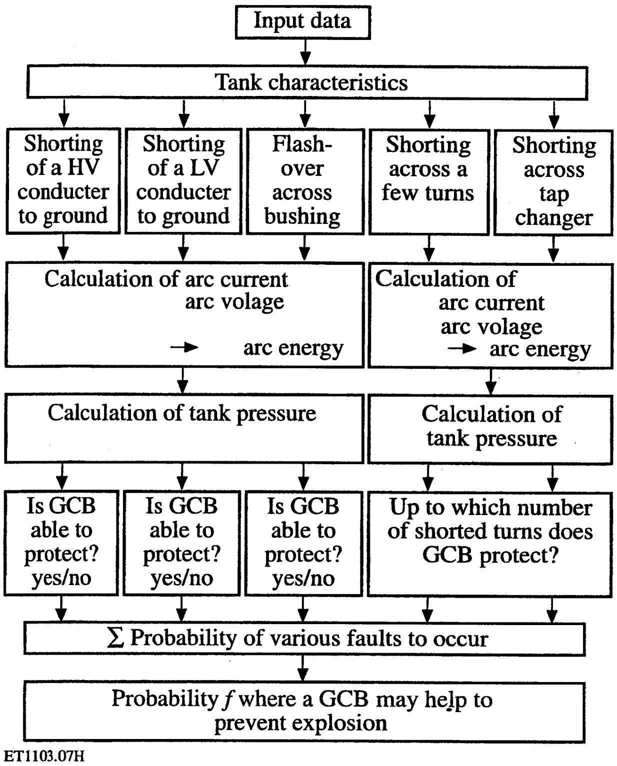

Fig. 7. Flow diagram of calculation procedure

3.3 Probability that a Generator Circuit Breaker is Able to Prevent Transformer Rupture

In order to express the usefulness of the GCB in our respect, a safety factor *f* has been defined which expresses the probability a GCB may prevent catastrophic damage of the transformer or the entire installation. *f* is calculated according to the procedure schematically shown in **Fig. 7**.

Applying the results for arc-current value, pressure rise and the statistical occurrence of the various fault location, the following procedure has been established with the aid of a computer code.

After input of the relevant data (i. e. net characteristic, breaking time of the switches, etc.) and calculation of the tank expansion coefficient, the code splits into two main paths.

One path is calculating faults where a complete coil is shorted. This part of the code is worked through for HV flash-over and for LV flash-over and for a fault at the bushing. The pressure values are calculated for the moments the HV breaker and the GCB, respectively, disconnect. For comparison the final pressure rise in case there is no GCB is calculated too. This leads to a pressure course for each type of failure, schematically shown in **Fig. 8**.

The interrupting times of the HV and the LV circuit breaker are indicated by t_1 and t_2, respectively. The dashed line represents the pressure rise if there was no GCB. If the tank withstand pressure lies higher than the permanent pressure after disconnecting both sides of the transformer, the GCB prevents tank cracking. If the pressure rise during the first and/or second time interval is high enough to meet the limit of the tank, the GCB is not able to contribute to transformer protection. This way the procedure supplies a yes/no decision for each type of fault involving an entire coil in the short circuit.

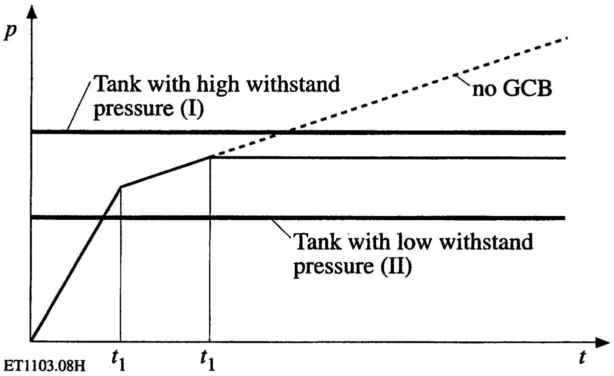

Fig. 8. Pressure rise inside the tank
(I) GCB prevents rupture of tank with high withstand capability
(II) GCB cannot prevent rupture of tank with low withstand capability

The other main path of the program calculates the pressure rise when only part of the winding is involved in the short circuit. The entire coil is thought to be split into a hundred portions and it is calculated up to which percentage of shorted turns the GCB is able to prevent tank rupture (**Fig. 9**). It is assumed that the probability for a certain number of windings being shorted is equal for each number of shorted turns.

Finally the yes/no decisions of each kind of fault being evaluated with the statistical probability of that specific fault to happen (as described in chapter 3.1.1) lead to an cumulative probability of the GCB being able to prevent transformer explosion.

4 Case Studies

For verification of the procedure above, three failure cases, where detailed data have been available, have been calculated and one of them is shown in the following as an example. The following data were applied:

- Transformer: 426 MVA, 22 kV/250 kV, $\varepsilon = 14$ %;
- Generator: Short-circuit impedance 23 %;
- System: Short-circuit power 10 GVA;
- Switching moments: HV-side $t_1 = 40$ ms,
  LV-side $t_2 = 80$ ms after fault initiation.

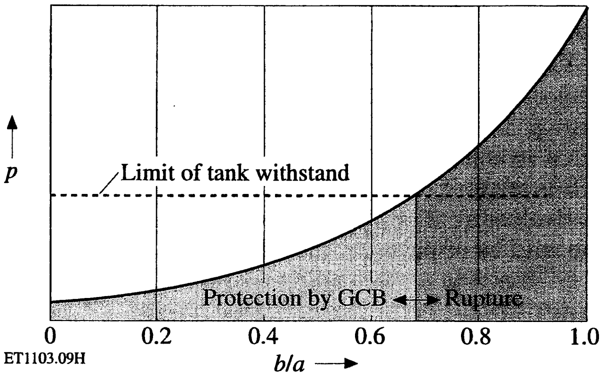

Fig. 9. Final pressure depending on amount of shorted turns

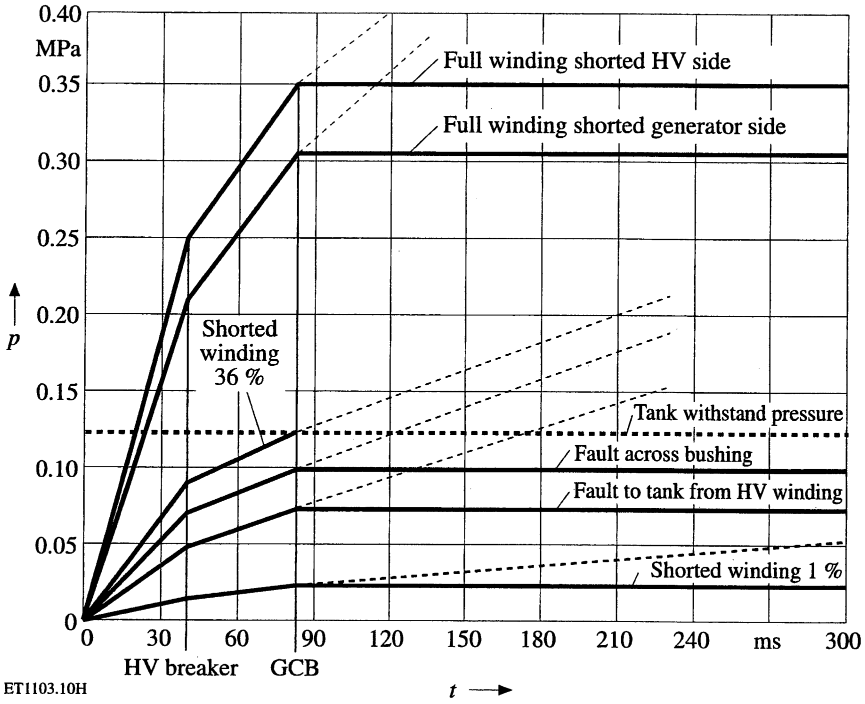

Fig. 10. Pressure rise for different kinds of faults

The result of this calculations is shown in **Fig. 10**. The full lines show the build up of pressure when a GCB is installed. In this case the pressure does not rise any more after the disconnecting time t_2 of the GCB. The dashed lines illustrate how the pressure would increase if there was no GCB installed.

The figure shows that the pressure rise for a LV fault is very steep so that the bursting pressure is already reached before even the HV switch is able to disconnect. In this case it does not make any difference if a GCB is installed, the tank normally will burst anyway. The reason for that is that the arc current is very high at a LV fault.

The curves for HV fault and bushing fault are parallel, because along the bushing there is assumed to be a shorter arc path (400 mm) than at any other HV flashovers between connecting conductors at the HV side. These curves exceed the limit of the tank withstand pressure after the breaking moment of the GCB, i. e. the GCB is able to prevent tank explosion for these cases.

Fig. 10 also shows how the pressure rises if 1 % or 100 % of the HV coil is short circuited. Where at 100 % the GCB cannot help, the pressure rise at 1 % is uncritical. In the considered case up to 36 % of the coil can be shorted before the GCB looses its protective function.

For a winding fault with more than 36 % of the turns being shorted, the pressure rise is very steep so that the bursting pressure is already reached before the LV switch is able to disconnect the line. In this case the GCB is not able to prevent tank rupture.

Evaluating all the different kinds of faults with their probabilities of occurrence, the calculation shows that the GCB is able to prevent tank explosion with a probability of 73 %.

Return of field experience in this specific case showed that the bushing was blown out 160 ms after fault initiation and the tank was damaged already with serious cracks but which were not open. As the according curve crosses the tank withstand limit at approximately 120 ms, this observation matches sufficiently with the calculation.

In two other cases, where sufficient recording was available, the transformer exploded as could have been predicted by calculation. In a fourth case, the GCB cleared before tank rupture, which also can be shown by calculation.

5 Concluding Remarks

The procedure presented in this paper shows how estimation of pressure rise caused by a fault arc inside a power transformer is possible. A variety of fault types and fault locations have to be taken into account. Considering the somewhat wide scatter of the relevant parameters as arc energy, gas production, and mechanical tank withstand characteristics, exact calculations are not feasible.

Nevertheless, using statistical mean values, it is possible to provide an adequate result which gives the extent to what a generator circuit breaker (GCB) between generator and step-up transformer prevents severe damage of the transformer and consecutive jeopardy and/or damage of the entire installation.

Case studies for existent plants show that the potential of a GCB to prevent damage is significantly high, up to a probability of more than 80 %. The studies demonstrate that for a typical application the use of a GCB can greatly reduce the probability of a tank rupture during an internal fault. This will increase the reliability of the facility by prevention of fire and the safety of personnel as well. Short relaying time and interrupting time of both the GCB and the breaker at the high-voltage side is essential.

The estimation above provides a step in the process of decision on the profitability of a GCB in new power plants or in case of retrofit.

6 List of Symbols

a	total length of transformer coil
A	tank-expansion coefficient
b	length of transformer coil
C	gas-production rate
C_0	gas-production rate at normal air pressure
f	safety factor
h	axial displacement
I	current
I_{arc}	arc current
$I_{\mathrm{g(en)}}$	current fed by generator
$I_{\mathrm{n(et)}}$	system current
I_{rs}	short-circuit current of intact transformer
m_1	coupling factor between LV winding and shorted turns of HV winding
m_2, m_3	coupling factors between shorted turns and intact turns of HV winding
p	pressure
p_0	normal air pressure
t	time
t_1	moment of system isolation
t_2	moment of clearing by GCB
t_3	moment of current zero after de-excitation of generator
T_1	time where arc fed by system as well as by generator
T_2	time where arc fed by generator only (with GCB)
T_3	time where arc fed by generator only (without GCB)
U	voltage

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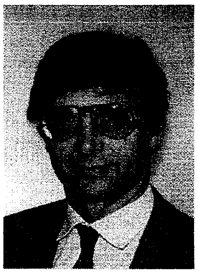

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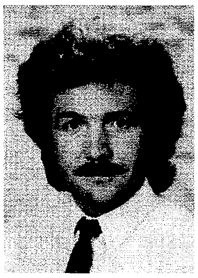

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