A probabilistic approach to transformer explosion risk analysis

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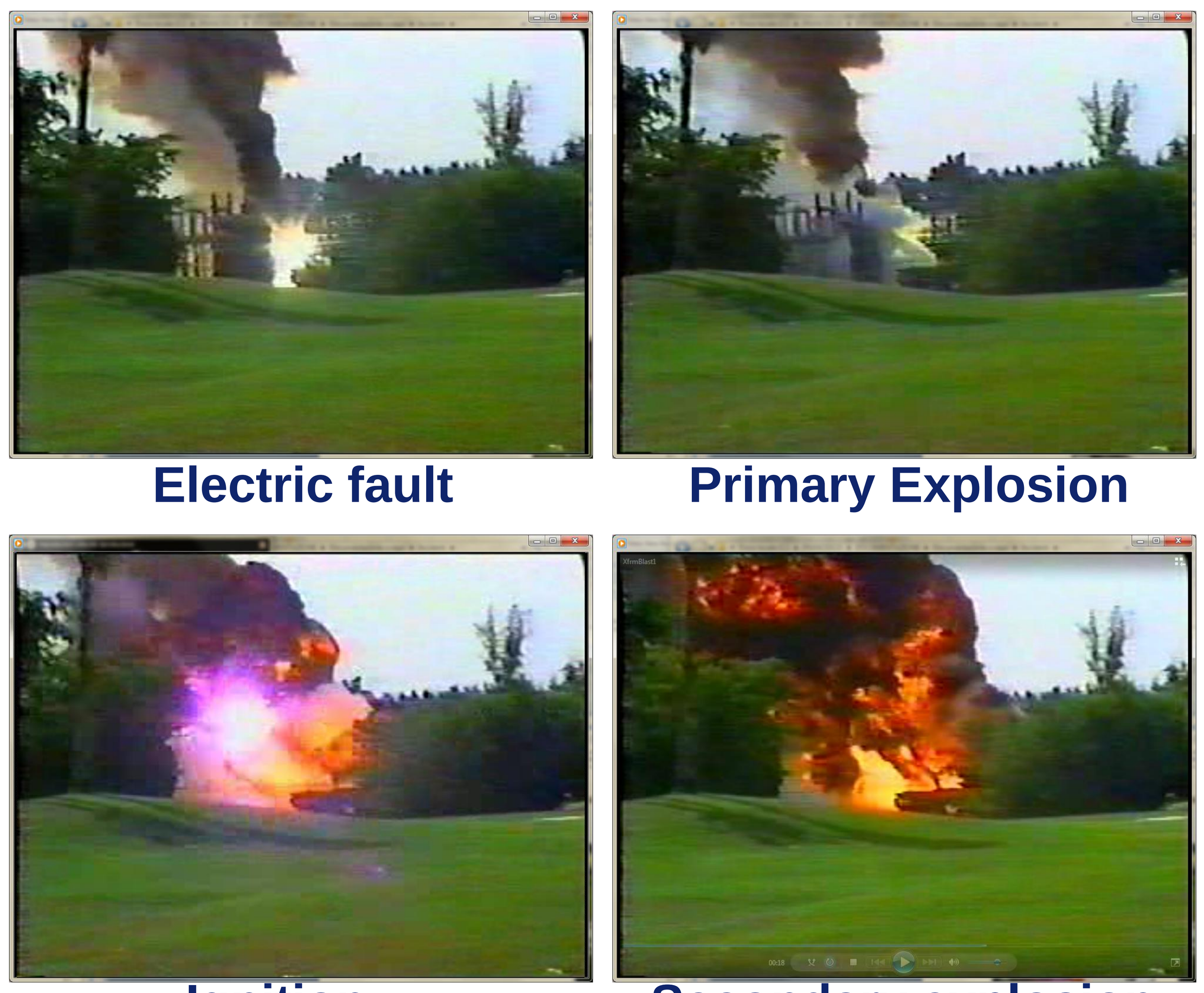
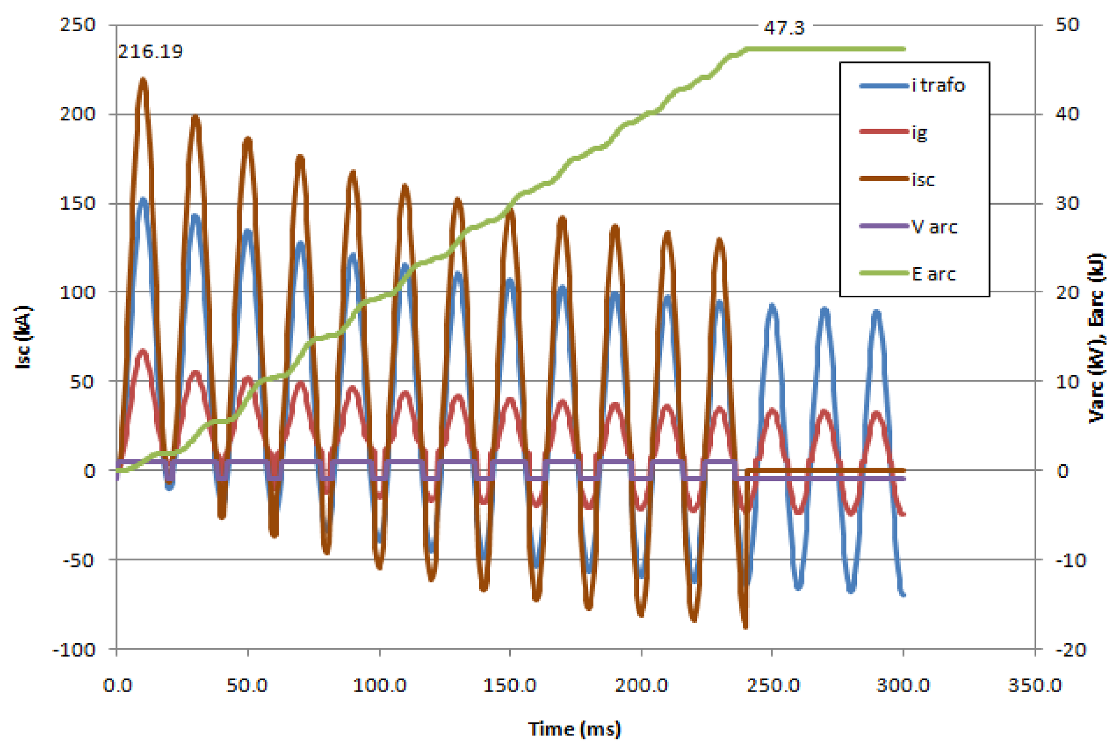
Introduction

Internal arcing fault in an oil insulated transformer can lead to severe accident scenario escalation. A certain amount of oil is decomposed into a saturated hydrocarbons gaseous mixture by means of a pyrolysis reaction; for severe faults, this can induce the structural failure of the transformer tank (primary explosion scenario): hydrocarbons mixture is violently released through the transformer tank breaches together with liquid oil; part of the liquid oil is turned into mist, mixing with hydrocarbons mixture and air. Such an explosive atmosphere may result in a very strong explosion if ignited (secondary explosion scenario).
For confined facilities, such as underground hydropower plants, the consequences of an explosion in terms of human and material damages may become very severe if pressure venting is not suitably optimized, with respect to both internal and external effects. Moreover, domino effect on subsequent fire scenario can be catastrophic.
Several events contribute in establishing a secondary explosion scenario, dealing with electrical, chemical, physical and mechanical aspects; a comprehensive, multidisciplinary methodological approach is required in order to properly estimate the potential of such scenario.
A methodology for Transformer Explosion probabilistic risk assessment was originally developed by Gexcon within the research project SEBK [1], and recently improved by including a more accurate definition of the electrical fault scenarios [2][3][4].



Electric fault — Primary Explosion — Ignition — Secondary explosion



Characterization of electrical internal fault

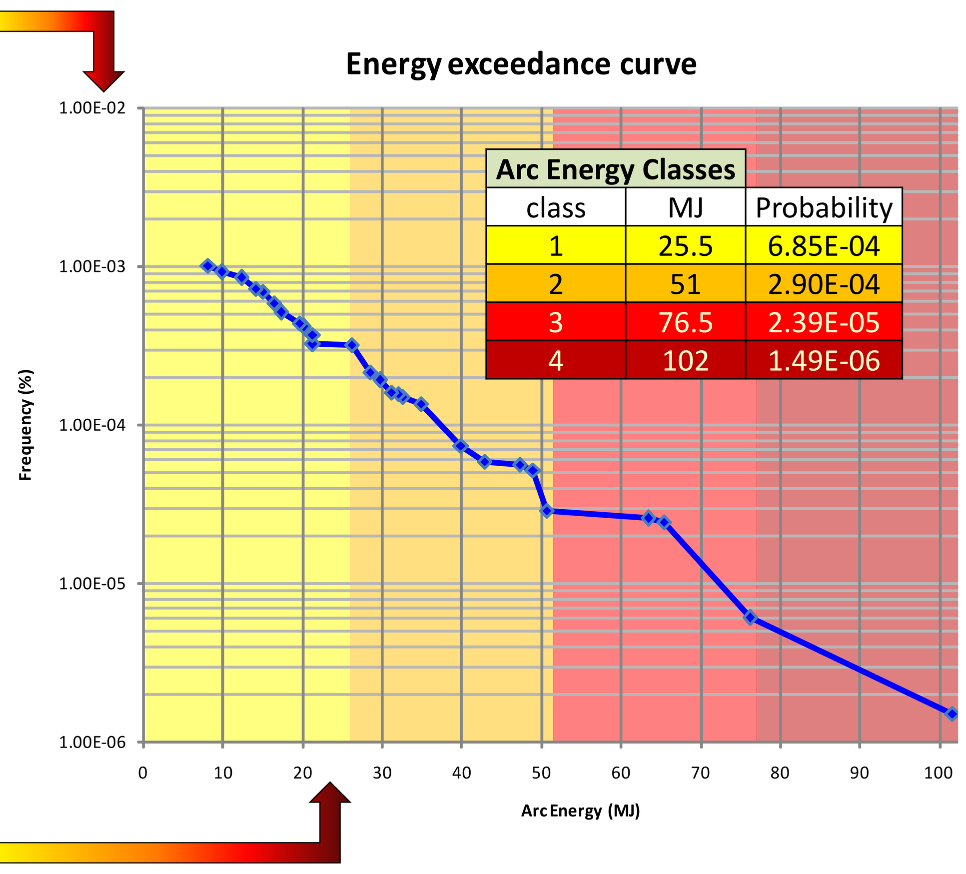
The first step in the probabilistic risk assessment methodology here proposed consists in the description of the electrical fault scenarios, in terms of internal arc energy quantification and definition of associated frequencies. The electric energy developed by an arc discharge is calculated according to the following expression:

$$E_{arc} = \int_0^{t_{max}} i(t) v_a(t)\, dt$$

Where i(t) is the current time history flowing in the arc, va(t) is the arc voltage time history, tmax(t) is the total time duration of the arc. The two time histories are calculated using asuitable equivalent circuit and according to the electrical parameters of the system.

	L (mm)	Probability t=80 ms	Probability t=150 ms	Probability t=240 ms
HV 1 arc	200	9.0%	3.0%	0.4%
	300	12.0%	4.5%	0.7%
	400	7.5%	2.2%	0.3%
HV 2 arcs	200	7.5%	1.5%	0.3%
	300	10.5%	2.2%	0.4%
	400	6.0%	1.8%	0.1%
Gen	50	7.5%	2.2%	0.3%
	75	10.5%	3.0%	0.4%
	100	4.5%	1.5%	0.1%

	L (mm)	Arc energy t=80 ms	Arc energy t=150 ms	Arc energy t=240 ms
HV 1 arc	200	8.2	14.2	21.3
	300	12.3	21.3	32.1
	400	16.4	28.5	42.9
HV 2 arcs	200	17.4	32.6	50.7
	300	26.2	49.0	76.2
	400	34.9	65.5	101.8
Gen	50	9.9	19.6	31.2
	75	15.0	29.8	47.3
	100	20.2	40.0	63.5



Arc Energy Classes		
class	MJ	Probability
1	25.5	6.85E-04
2	51	2.90E-04
3	76.5	2.39E-05
4	102	1.49E-06

Electric fault scenarios

A suitable set of electric fault scenarios should be defined, by varying arc length, arc duration and number of arcs. For each scenario, the cumulated arc energy is calculated by integrating the obtained current and tension transients. Within the framework of the probabilistic approach here proposed, the probability associated to each scenario should also be defined, meaning the probability of having a given scenario if an electric fault occurs. These probabilities should be based on statistics and operational record data available, as well as engineering judgment and experience. More than a rigorous mathematical function, these frequencies should be considered as a logical criterion to categorize and rank the different fault conditions considered, which allows to take into account all the information relevant to electric reliability of the plant under investigation into the risk evaluation procedure.

Oil Mist Classes		
class	oil x	oil mist (equivalent butane) fraction
1	1	20.2
3	3	60.6
7	7	141.5

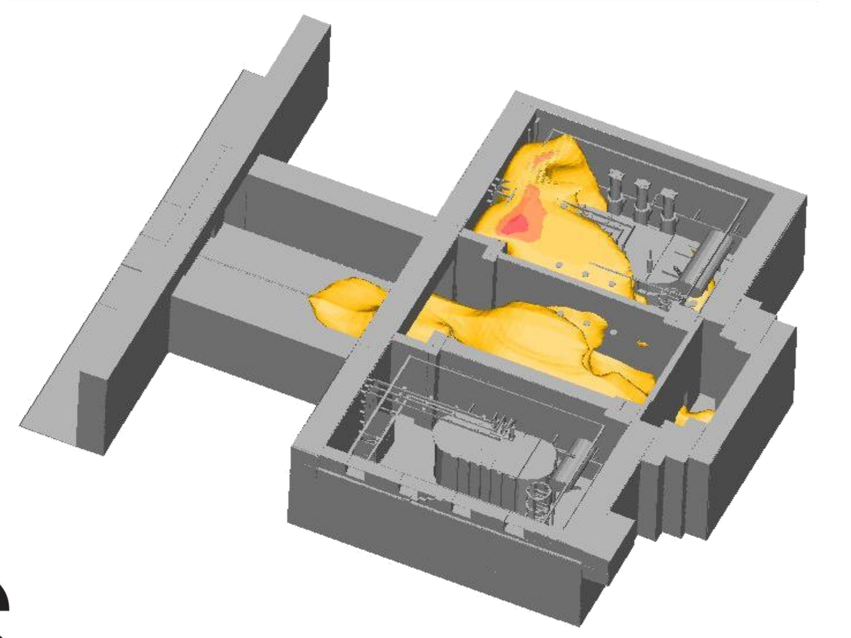
Gas cloud volume (m3)		Oil Mist Class 1	Oil Mist Class 3	Oil Mist Class 7
Arc Energy Class	1	31.8	65.2	132.0
	2	63.6	130.4	264.0
	3	95.4	195.6	395.0
	4	127.2	260.8	528.0

Explosion Scenario Probability (%)		Oil Mist Class 1	Oil Mist Class 3	Oil Mist Class 7
Arc Energy Class	1	3.08E-04	2.40E-04	1.37E-04
	2	1.01E-04	1.16E-04	7.25E-05
	3	5.98E-06	9.57E-06	8.37E-06
	4	2.99E-07	5.23E-07	6.73E-07

Secondary explosion scenarios

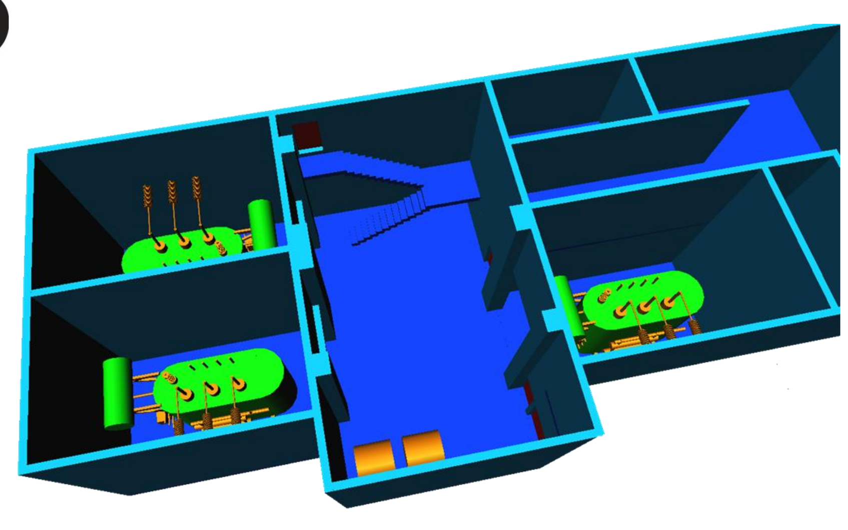
The arc energy values obtained for the considered electric fault scenarios should be grouped into a suitable number of arc energy classes, each one characterized by a given arc energy value. For each class, the probability is then calculated as the sum of the probabilities of all the scenarios in the class, multiplied by the reference transformer fault frequency.
Oil mist classes should also be defined in addition, each one characterized by a given oil mist amount and relevant frequency; the oil mist amount is commonly expressed in terms of multiples of the oil mist amount having the same combustion energy of the hydrocarbons in the mixture.
A suitable set of secondary explosion scenarios can be then defined, by combining the defined arc energy classes and oil mist classes, calculating the relevant fuel amount and defining the size and location of the consequent gas cloud, and finally defining a suitable location for ignition.

FLACS



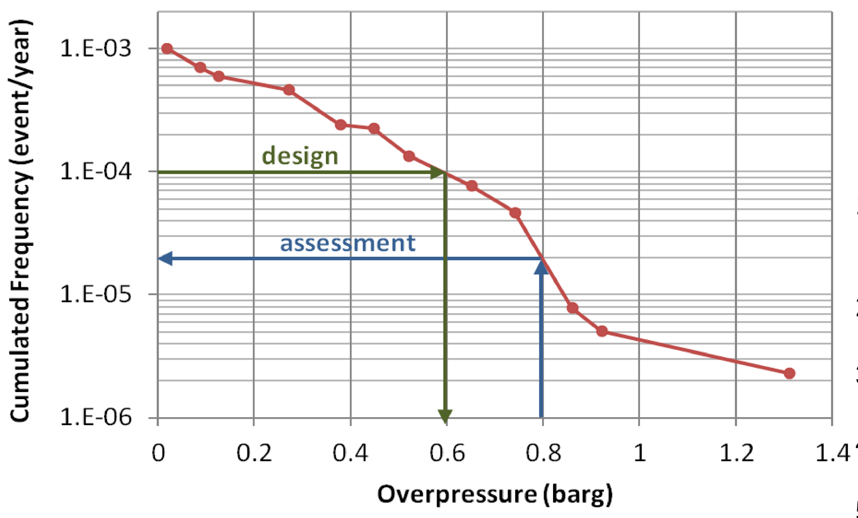
Estimation of explosion effects by means of CFD analyses with FLACS

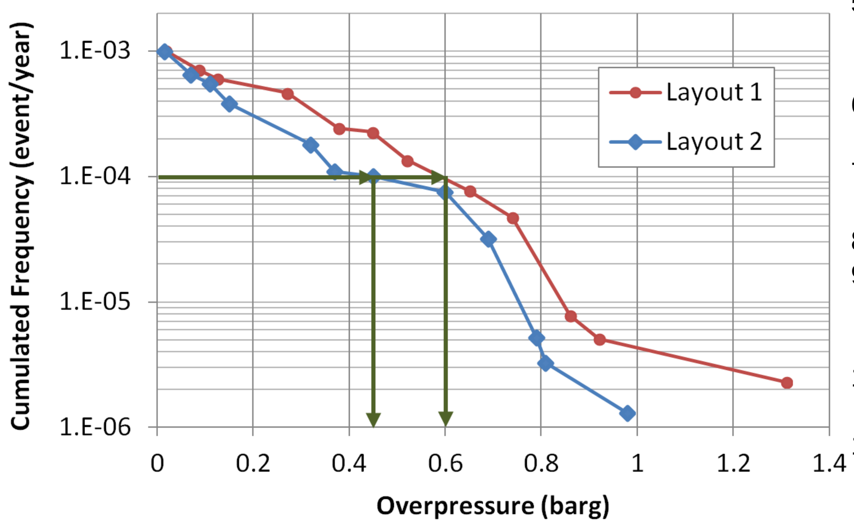
Within the proposed methodology, the effects of the secondary explosion scenarios are estimated by means of CFD analyses using the numerical code FLACS [8] by Gexcon, an advanced CFD tool for gas dispersion and explosion modeling in complex process areas. Once the geometrical model is developed, secondary explosion scenarios are defined in terms of gas mixture, gas cloud size and position, and ignition position. Numerical CFD analyses are carried out with FLACS, simulating the flame and pressure wave propagation for each considered secondary explosion scenario.



Exceedance curves for risk evaluation

In a design phase, Exceedance curve plots represent a suitable tool for the definition of Design Accidental Loads (DAL), once a return frequency in terms of number of events per year is established. In the example here, a design criterion 10E-4 events per year is adopted for the design of the concrete bay, and a DAL equal to 0.6bar is obtained from the exceedance curve plot; the design procedure is indicated by the green arrows in the plot.
Exceedance curve plots can be also effectively used in an assessment phase. In the same figure, an assessment procedure for a concrete bay designed for a DAL 0.8bar is indicated by the blue arrows; a cumulated frequency of 2E-4 is obtained from the exceedance curve plot, leading to a positive assessment result should a criterion 10E-4 events per year be adopted.
Exceedance curve plots can be used for layout optimisation; a clear indication of the effectiveness of a given modification in the layout of the considered plant is provided by the comparison between the exceedance curves obtained with the original and modified configurations.





References

1. SEBK (2002). *Sikkerhetstiltak mot Eksplosjon og Brann i Kraftforsyningen - Safety Measures to prevent Explosion and Fire in Electrical Power Plants*, Phase 1÷5. Project Reports
2. F.Chillè, A.L.Fuglestad (2012). *"Transformer explosion risk assessment using FLACS code"*, Brannforum 2012, Trondheim, 6-8/02/2012
3. A.Fracchia (2012). *"More accurate input data for FLACS analysis in an Electrical Origin Explosion"*, Brannforum 2012, Trondheim, 6-8/02/2012
4. F.Chillè, F.Duarte, A.L.Fuglestad (2012). *"Transformer explosion risk assessment of Frades II HPP"*, Hydro 2012, Bilbao, 29-31/10/2012
5. Kawamura T., Ueda M., Ando K., Maeda T., Abiru Y., Watanabe M., Moritsu K. (1988). *Prevention of tank rupture due to internal fault of oil-filled transformers.* Proc. of CIGRE International Conference on Large High Voltage Electric Systems, Paris, 28/8-3/9/1988
6. CESI (1998). *Indagine sui gas prodotti con archi interni nei trasformatori in olio*. Rapporto di Prova GPS-98/031632
7. CESI (2005). *Caratterizzazione dei principali componenti di sottostazioni elettriche con riferimento agli scenari incidentali di esplosione ed incendio*. Rapporto RdS A5030345
8. GexCon: FLACS-98 Manuals
9. IEEE Power Transformer Subcommittee (2010). *"Power Transformer Tank Rupture and Mitigation - Current State of Practice and Knowledge"*, Investigation Report, Houston, 09/03/2010
10. Marc Foata (2010). *"Power Transformer Tank Rupture - a Utility's experience"*, Hydro Quebec, IEEE Transformers Committee, Houston, 03/2010
11. Arne Petersen (2008). *"Risk Assessment for Explosive Failures in Transformers and Strategies to Reduce such Risks"*, Cigre APA2 Transformer Conference, Sydney, 31/03/2008

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