DETERMINACIÓN DE LOS MODOS DE FALA DE TRANSFORMADORES CONVERTIDORES EN SISTEMAS HVDC

Determination of the fault modes of hvdc converter transformers

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RESUMEN

En este artículo se presenta el uso de los árboles de fallas para el análisis de la confiabilidad de los transformadores convertidores en sistemas HVDC. Como principales resultados, se identifican los modos de falla relevantes de varios de los componentes del transformador, los cuales indirecta o directamente pueden causar fallas del sistema HVDC. El modelo del árbol de falla se analiza usando un software de libre distribución.

La metodología y los resultados de la aplicación de la misma, son útiles para evaluar la confiabilidad de transformador convertidor, dada su importancia en un sistema HVDC.

PALABRAS CLAVES: transformador convertidor, árboles de falla, sistemas de transmision HVDC, confiabilidad, modos de falla.

ABSTRACT

The use of fault tree theory for analyzing the reliability of HVDC converter transformers is discussed in this paper.

As main results, the relevant failure modes of several components of the converter transformer that directly or indirectly cause the failure of the HVDC system have been listed. The fault tree model is analyzed by using a free software tool and used to identify several critical components.

The results and methodology are useful to evaluate reliability in HVDC systems, principally in the converter transformer that is an important component in the HVDC transmission systems.

KEYWORDS: *Converter transformers, fault trees, HVDC transmission system, reliability, fault modes.*

1. INTRODUCTION

Since transmission and distribution of electrical power started, the technology began to look for economic and safe transmission systems. At the beginning, the best option was the AC transmission. However, high-voltage AC transmission links have disadvantages in opposition to high-voltage DC transmission links which motivate their development as a supplement to the AC transmission systems [1][2].

One of the advantages of the HVDC systems is related to the reduction of transmission power losses, and consequently the cost per megawatt also decreases [2]. Such systems can be viewed as an arrangement of several sub-systems, every one has particular functions. These functions have to work according to specific parameters to warrant an optimal transmission (loss levels, maintenance cost, safety and quality, among others)[2]. As a consequence, preliminary reliability information of every sub-system is required if a HVDC system is considered or evaluated. In this way, it is possible to predict a possible contingence (failure of one/more than one component in the system) and the alternatives to solve it. Besides, it is possible to estimate the necessary resources to solve the contingences, the system restoration time and the failure importance [2].

It is well known that one of the most critical components in the HVDC system is the converter transformer. Thereby if the converter transformer collapse all the system could also fail. The most noteworthy studies about converter transformers are presented in [1][2][6][7]. These studies deal with the main characteristics of the HVDC converter transformer and the mode and cause of failures.

On the other hand, fault tree analysis could be described as an analytical technique, whereby an undesired state of the system is specified (usually a critical state from a safety standpoint). Then, the system is analyzed in the context of its environment and operation, to find all possible ways in which the undesired event could happen [4][5]. The fault tree itself is a graphic model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event called “top event” [5][8].

The reliability analysis using fault trees have been discussed for different researchers. Some of the most important research in fault trees are presented in [3][4][5]. These deal principally with the construction of

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"fault trees", and the use of this methodology to evaluate reliability in all type of systems.

In this paper, the analysis of the reliability of HVDC converter transformers is performed using the fault three theory. The main results are the most critical "minimal cut sets" in the converter transformer system. As additional results, the reliability indexes, the failure rates for every part and the critical fault sets (general modeling of the converter transformer failures) are also given.

As contents, in section 2 the principles of the HVDC systems and the reliability analysis are disused. Section 3 is devoted to the converter transformer and its characteristic, functions, main components and fault modeling, while section 4 presents the principles to get the different models obtained for the converter transformer. In section 5, the result and analysis of the proposed approach are presented. Finally the most relevant conclusions of the presented research are given.

2. BASIC ASPECTS OF HVDC SYSTEMS AND RELIABILITY ANALYSIS

2.1. HVDC transmission systems

The HVDC transmission system has three main parts: one converter station at the beginning of the transmission line, and used to convert alternating current from the power network to direct current; the transmission either overhead line used to connect the high voltage from the converter station AC/DC to the converter station DC/AC; and finally, the converter station at the end of the transmission line, used to convert direct current back into alternating current and send it to the end customer using transmission or distribution systems [1][2].

a. HVDC Principles for the Converter Theory

The most common HVDC converter station is built like a 12-pulse circuit. This is a serial connection of two 6-pulse converter bridges which require two 3-phase systems, spaced everyone of each other 30° electrical [1][2]. The figure 1 shows a 12-pulse bridge.

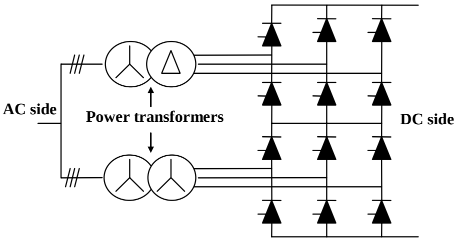

Figure 1: Converter/inverter station in a 12-pulse bridge

b. Main HVDC Schemes.

The HVDC links can be arranged in three different types: monopolar, bipolar and homopolar [1][2][9]. The most common configurations are the monopolar and bipolar [1][2]. Monopolar configuration with ground or sea return electrode which is mostly used for long distances [1][2]. Monopolar configuration could has a metallic return conductor to carry return current between converters at the opposite ends of the system. This configuration is used principally when existing infrastructures or environmental constraints prevent the use of electrodes, and in these cases the metallic return path is used [1][2].

The bipolar configuration with ground return path is a very common configuration for transmission systems. This configuration provides a very high flexibility during contingences or maintenance. Finally, the bipolar configuration with metallic return would be a good option when the transmission distance is relatively short. This configuration uses a dedicated HVDC metallic return conductor, which is an alternative to a ground return path with electrodes [1][9].

c. Main Components for HVDC Station.

The main components in the HVDC station are [1][2][9]: i)Converter building (Valve hall) contains bridges connected with converter transformer through the building's wall. The DC side windings of the converter transformers are connected to the converter bridges. ii)AC switchyard, which consists of circuit breakers and disconnectors used to limit the alternating current before going to the converter building; besides they have to clarify faults in the transformer. iii)Shunt capacitor banks, which help to compensate the reactive power consumed by the converters. iv)AC filter banks, used to absorb the harmonic currents generated by the HVDC converter. v)DC switchyard which consists of a DC filter and a smoothing reactor. The DC filter reduces the harmonic current on the DC side of the converter station. The smoothing reactor prevents intermittent current and resonance in the DC circuit, limits the DC fault currents and reduces harmonic currents. vi)HVDC converter transformer used to transform the AC system voltage to which the DC system is connected.

2.2. Main used definitions of reliability

Reliability is a term that describe the ability of an equipment to perform its function (using quantitative indexes) under given environmental and operational conditions and for a stated period of time [2][5]. The reliability is defined through the mathematical concept of probability to explain the particular type of performance.

Availability is the ability of an equipment to perform its required function at a stated instant of time or over a stated period of time. The availability $A(t)$ at time t is the probability of found an equipment functioning at time t. Equation (1) gives the average availability.

$$A_{av} = \frac{MTTF}{MTTF + MDT} \tag{1}$$

Where, MTTF and MDT is Mean Time To Failure and Mean Down Time, respectively.

Other common terms related to reliability analysis are: i)Failure rate is the rate at which failures occur as a function of time. ii)Repair rate is the rate that the out of service component will return in service mode during a given time interval. iii) Replace rate is the rate that the spare component will be replaced the failed unit and bring the system back to service mode during a given time interval.

Similarly, distribution function of a continuous random variable *T* with density function *f(t)* is defined by (2). The density function is then defined by (3).

$$F(t) = P(T \le t) = \int_0^t f(u)du \quad for \quad t>0 \qquad (2)$$

$$f(t) = \frac{d}{dt}F(t) = \lim_{\Delta t \to 0} \frac{F(t+\Delta T) - F(t)}{\Delta t} \qquad (3)$$

The reliability function as the probability that the item does not fail in the time interval (0, t] is defined by (4).

$$R(t) = 1 - F(t) = P(T>t) \ for\, t>0 \qquad (4)$$

Finally, the failure rate function, defined as (5) and the mean time to failure (MTTF) is given by (6).

$$z(t) = \frac{f(t)}{R(t)} \qquad (5)$$

$$MTTF = \int_0^\infty tf(t)dt = \int_0^\infty R(t)dt \qquad (6)$$

2.3. Fault tree theory

A fault tree shows the relation among components from a system by means of a diagram, according to the Boolean logic. Using this diagram, it is possible modeling all the system conditions, which could be the cause of the “top event” or main fault. The “event” means dynamic move for an element or condition, that affects the normal system behavior [8][10][11]. All the elements in a system can be affected by operations, environmental conditions, human mistakes or in general all kind of agents involved in the system operation [4][8].

In a fault tree, the basic components are the logic gates. The fault trees are conformed by using event, transfer and logic gate symbols. The figure 2 contains all the symbols used in the fault tree analysis.

The first step to make the quantitative analysis in the fault tree is to get all the “minimal cut sets”. A minimal cut set contains all the events that could be cause for the “top event”. When the minimal cut sets are known, it is possible to make the probabilistic analysis [4].

The following are the common events considered in a fault tree: i) Intermediate event used to specify a failure that occurs due to one or more causes acting through logic gates below it in the fault tree. ii) Basic initiating event used to specify a failure event that does not require any further development i.e. it is a “leaf” of the fault tree and has no gates or events below it in the tree. iii) Undeveloped event used to specify a failure event that is not developed as far as it could be, either because the event is not important in this fault tree, or because there is not enough information available. iv) External event that specify a failure event that is expected to occur and is therefore not directly a failure. The event can only has a probability attached to it of 0 (Failed) or 1 (Working). v) Conditioning event that specify certain conditions upon any logic gate.

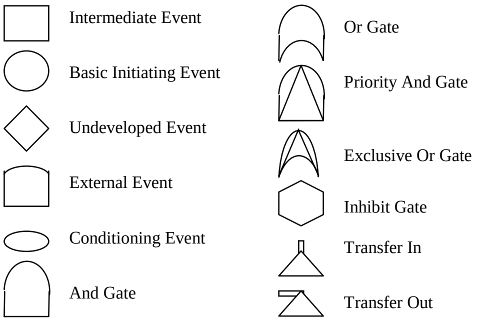

Figure 2: Fault tree most commonly used symbols

The most used logic gates in fault trees analysis are: a) *And* gate used to show that the output fault will only happen if all of the inputs occur. b) *Or* gate used to show that the output fault will only occur if one or more of the input faults take place. c) *Priority And* gate, where the output only occurs if the input faults take place in a certain order. The sequence of events is usually stated in a conditioning event, situated to the right of the gate. d) *Exclusive Or* gate where the output only occurs if exactly one of the input faults happens. e) *Inhibit* Gate where the output fault only occurs if the single input happens and the attached conditioning Event is satisfied. This gate is in effect a special case *And* gate.

Finally, the following are the transfer symbols: a) *Transfer In*, used to depict a sub-tree that has been stored in a separate file. b) *Transfer Ou*t that is used to depict that the tree shown below a transfer out symbol is a sub-tree of a fault tree that is stored in a different file.

3. CONVERTER TRANSFORMER BASICS

The converter transformer, transforms the AC voltage from the busbar to the voltage required by the converter. The 12-pulse converter requires two 3-phase systems, everyone spaced from the another 30° or 150° electrical. To obtain this, it is necessary to place a transformer on each network side in the vector groups Yy0 and Yd5; this condition ensure the voltage insulation necessary to connect converter bridges in series on DC side [1].

There are some considerations to choose the design of the transformer, like the dimensions, weight and transportation required, among others. According to these considerations it is necessary to use some of the next configurations [4]: i) Single-phase-two-winding transformer; ii) Single-phase-three-winding transformer; iii) Three-phase-two-winding transformer; iv) Three-phase-three-winding transformer. According to the type of used transformer it is possible to have the following different arrangements: i) Two three-phase-two-winding transformers. ii) Six single-phase-two-winding transformers. iii) One three-phase-three-windings transformer. iv) Three single-phase-three-winding transformers

3.1. Main components of the converter transformer

The main components of the HVDC transformers are following presented [1][6]:

a. Core. HVDC converter transformers are usually 1-phase, whereby the valve windings for the star and delta connection are configured either for one core with at least two main limbs or separately for two cores with at least one main limb.

b. Windings. The shape of the winding conductor in power transformers is usually rectangular in order to utilize the available space effectively. In concentric winding arrangements, star or delta valve windings lying directly on the core have proven optimal conditions.

c. Tank. The tank is a physical protection for the active part and the support structure for accessories, besides it contains the oil. For HVDC transformers with delta and star valve winding in one tank, the valve bushing must be arranged so that their ends conform to the geometry of the thyristor valve towers.

d. Bushings. Terminals device in form of bushing brings the connection from the transformer insulation medium to the external insulation medium, which in most cases is composed by air, but could also be oil in cable termination box or SF6 in gas insulated switchgear.

3.2. Typical failures of the converter transformers

In a general model for failures it is possible classify the fault events according to the faulted part as: i) Bushing, ii) Valve winding, iii) AC winding, d) Static shield, iv) Load Tap Changer (LTC), v) Core and Magnetic field, and vi) Other internal connections.

According to these fault events is obtained a general fault tree model as it is presented in figure 3.

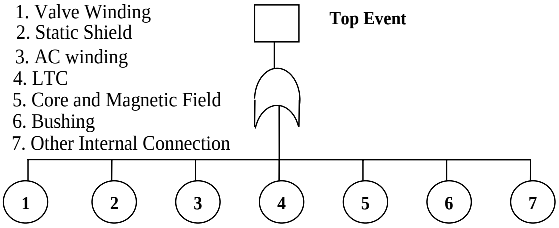

Figure 3: Proposed generic fault tree for the converter transformer.

Beginning with a general model and applying particular causes of faults mechanical, dielectric, thermal, induced current, human operational errors and those produced by unknown causes it is possible to obtain particular models [6]. As example, the particular model in the case of AC winding fault is shown in figure 4.

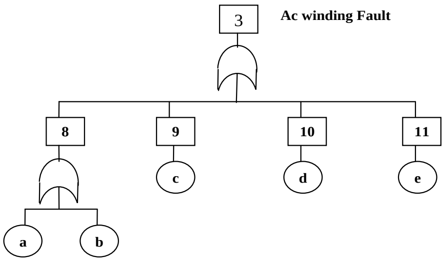

Figure 4: Particular model or fault tree of a winding fault.

Where numbers in figure 4 correspond to: Number 8 is related to low insulation resistance, Number 9 is associated to unexpected overvoltage, Number 10 is non symmetrical voltage on the secondary side and 11 corresponds to triggering of a over current relay. Letters a, b, c , d and e, are the events presented in table 4.

4. FAILURE MODELING FOR THE CONVERTER TRANSFORMER

4.1. Test system

The reliability data of the proposed power system is given in table 1. As additional information, the power transformers failures rates are given in table 2.

Component	Failure rate (f/yr)	Repair time (hours)	Installation time (minutes)
Valves (B)	0,250	96,0	45
Generating Units	0,500	87,6	--
Transformers	0,012	168,0	--
Transmission Lines	1,500	4,0	--
Pole Equipment (P)	0,040	8,0	--
Filters (F)	0,012	168,0	--

TABLE 1. Reliability data

HVDC transformer component	Failure rate (%)
Windings	34,2
Bushings	2,50
Main insulation	11,4
LTC	1,30
Winding admit	19
Bushing admit	6,30
Tank	1,30
Unknown	1,30
Switchboard	17,70
Core	3,80
Auxiliary equipment	1,30

TABLE 2. Power transformers failures rates

4.2. Fault tree

From tables 1 and 2, and making a particular model with the principal faults on the system, it is obtained a fault tree for the relevant failure modes for the converter transformers. These failures directly or indirectly would cause the failure of the HVDC system.

The fault tree model is implemented by using an open software tool called *OpenFTA*. The unavailability or failure rate and the repair time of each component are used as the input data for the basic events from table 2. In addition, the reliability indexes of the most important events are computed to evaluate the reliability of the system. Finally, by using the fault tree model, several critical components were identified.

5. RESULTS AND ANALYSIS

5.1. Results for the general model

The results for the general model and using data from tables 1 and 2, are given in table 3. As additional information, the number of primary events is seven, the probability of at least 4,137080E-001 one component failure, and the probability of top event is 4,137080E-001 (+/- 4,137080E-003).

Event	Failure contribution	Importance (%)
AC Winding	3,410609E-001	82,44
Bushing	2,478111E-002	5,99
Core and Magnetic Field	3,789565E-002	9,16
LTC	1,340414E-002	3,24
Other Internal connection	1,419018E-002	3,43
Static Shield	1,228713E-002	2,97
Valve Winding	1,224576E-002	2,96

TABLE 3. Results from the general model of the transformer

According to the results for the general model, the most critical part is the AC winding due to the high importance obtained (82,44%). Possible causes for failure in the converter transformer could be: i)Bushing failures could happen due to the high humidity condition add to mechanical stress because of internal flashover; ii)Valve windings are damaged principally by the harmonic induces eddy current heating; iii)Faults on LTC are cause because of high operating temperature driving the device to the mechanical damage; iv)AC windings are affected principally by the excessive moisture creating a possible turn-to-turn short; and v)The static shield could be affected by another external condition (like earthquake, or another natural phenomenon)

5.2. Results for particular models

The results for every particular model obtained using data from tables 1 and 2, are presented in tables from 4 to 10.

a. Results for the AC winding model

Event	Failure contribution	Importance (%)
Earth fault (a-8	1,128054E-001	14,53
Oil deficiency (b-8)	1,110198E-001	14,30
Winding rupture (c-9)	3,428416E-001	44,16
Winding rupture (d-10)	3,391150E-001	43,68
Winding rupture (e-11)	3,339134E-001	43,01

TABLE 4. Results from the AC winding model faults

The model of the AC faults is shown in figure 8. As additional information, the number of primary events is five, the probability of at least 7,763623E-001 one component failure.

According to the results, the most critical cause is the winding rupture, because it is the most probably cause for the AC winding fail, besides is a very important fail because affects to the converter transformer in a very serious way.

b. Results for the bushing model

Event	Failure contribution	Importance (%)
Arcing in active part	2,474181E-002	50,11
Earth failure on one phase	2,521088E-002	51,06

TABLE 5. Results from the bushing model faults

Additionally in the case of bushing model faults, the number of primary events is two, the probability of at least 4,935E-002 of one component failure and the probability of top event is 4,937E-002 (+/- 4,937E-004). From table 5, the "arcing in active part" and the "earth failure on one phase" have almost the same importance for conducing to the top-event (bushing fault).

c. Results for the core and magnetic field model

Event	Failure contribution	Importance (%)
Core	3,752049E-002	61,56
Reflection from walls and other elements	1,216551E-002	19,96
Low frequency	1,221427E-002	20,04

TABLE 6. Results of the core and magnetic field model faults

The number of primary events is three and the probability of at least 6,094947E-002 one component failure. From table 6, this model suggest that the most critical cause to the top-event happen is the core (61,56%).

d. Results for the LTC model faults

Event	Failure contribution	Importance (%)
Operation of tap-changer failed	1,279965E-002	33,25
Sudden pressure rise tap-changer compartment	1,334244E-002	34,66
Tap-changer or bolted links incorrectly connected	1,283045E-002	33,33

TABLE 7. Results from the LTC model faults

Additionally, the number of primary events is three, the probability of at least 3,84952E-002 of one component failure. From table 7, the top-event could happen almost with the same probably for every one of the primary events and their importance is in the same.

e. Results for the internal connections model

Event	Failure contribution	Importance (%)
Internal failure in the transformer	1,195387E-002	16,03
Failure in current transformers feeding the relay	1,261010E-002	16,91
Triggering and alarm incorrectly set	1,342293E-002	18,00
Incorrect thermometer operation	1,321413E-002	17,72
Relays incorrectly timing	1,284873E-002	17,23
Leakage in cooler	1,295313E-002	17,37

TABLE 8. Results from the other internal connections model faults.

As additional information, the number of primary events is six, the probability of at least 7,457185E-002 of one component failure. From the presented results, in the case faults in internal connections, it is notice that the same importance every one of the auxiliary equipment, because they have the same percentage rank for driving to the top-event.

f. Results for the static shield model faults

From the results, the number of primary events is two, the probability of at least 2,484400E-002 one component failure. From table 9, the top event could happen with the same possibility if some one of the primary events occurs (Lose accessories or elements, or tank fault).

Event	Failure contribution	Importance (%)
Lose accessories or elements	1,188289E-002	47,83
Tank	1,308533E-002	52,67

TABLE 9. Results from the static shield model faults

g. Results for the valve winding model faults

Event	Failure contribution	Importance (%)
Short circuit in the system on	1,120501E-002	2,27

the secondary side		
Blown fuse in 1phase	1,904358E-001	38,58
LV installation	1,209351E-002	2,45
Non-symmetrical load on the secondary side	1,890537E-001	38,30
No voltage applied in one of the phases on the primary side	1,914230E-001	38,78
Too high oil temperature	1,194543E-002	2,42
Too high water temperature	1,041523E-002	2,11

TABLE 10. Results from the valve winding model faults

As additional results, the number of primary events is seven, the probability of at least 4,936127E-001 of one component failure. From table 10, the valve winding faults occur principally because of the eddy currents, and harmonics produce those creating overheating and driving a fault. However, exist another type of causes for driving to a fault in valve winding, like "*no voltage applied in one of the phases on the primary side*" with a percentage rank of 38,78%.

Finally, according to the results obtained from all of the presented models, the most critical part of the HVDC converter transformer system is the AC winding and valve winding set. This component contributes to the top-event in the principal model (model including all the sub-systems) with the most significant percentage rank.

6. CONCLUSIONS

According to the research presented in this paper, it is possible to notice how from the general model of the converter transformer, useful information to evaluate reliability in the HVDC system is obtained. Besides were proposed seven different particular models of fault modes obtaining information about the most critical minimal cut sets. This results are useful when is necessary to find weak points in the analyzed system.

The reliability evaluation using fault trees requires the previous knowledge of information about the system and the basic events, like the unavailability or failure rate and the repair time of each component.

From the results, the valve winding and winding set are identified as the most critical cut set, according to the importance to the occurrence of the top event (35,72%).

Finally, the research presented in this paper is useful to maintain the service continuity at the power systems.

7. REFERENCES

[1] J. Arrillaga "*High Voltage Direct Current Transmission*" IEE Power Engineering Series. 1998.

[2] R. Leelaruji, "*Availability Assessment of HVDC Converter Transformers Using Markov Modeling*". Master Thesis, The Royal Institute of Technology, School of Electrical Engineering, Stockholm, April 2007.

[3] J. Gómez, L. Caraza, R. Rea. "*Construcción automática de árboles de fallas utilizando sistemas expertos*". BOLETIN IIE VOL. 17, pag 157-163. N°3-1993.

[4] M. Schwarzblat, J. Arellano, G. Martinez. "*Análisis de confiabilidad en el IIE utilizando la teoría de árboles de falla*". BOLETIN IIE VOL. 5, pag 166-171. N°4-1981.

[5] L. Yu "*Fault Tree Analysis and Reliability Assessmentof Auxiliary Power Supply system for an HVDC Plant*". Master Thesis, The Royal Institute of Technology, School of Electrical Engineering, Stockholm, May 2007.

[6] ABB Transformers. "*Transformer Handbook*" ABB. www.abb.com/transformers.

[7] J. Alan C. Forrest, B. Allard "*Thermal Problems Caused by Harmonic Frequency Leakage Fluxes in Three-Phase, Three-Winding Converter Transformers*". IEEE transactions on power delivery, vol. 19, no. 1, january 2004.

[8] M. Rausand, A. Hoyland. "*System Reliability Theory Models, Statistical Methods and Applications*". John Wiley and Sons Inc., Norwegian University of Science and Technology, 2nd edition, January, 2004.

[9] V. Sood, "*HVDC and FACTS Controllers Applications of Static Converters in Power Systems*". Kluwer Academic Publishers, 1st edition, May, 2004.

[10] R. Billinton, R. Allan "*Reliability Evaluation of Engineering Systems*". University of Saskatchewan and University of Manchester Institute of Science and Technology. Pitman Advanced Publishing Program, London 1982.

[11] FTA. "*Manual for OpenFTA*". www.openFTA.com.